COMPARISON OF EMPIRICAL METHODS FOR TAILINGS DAM BREAK ANALYSIS: CASE OF STUDY THE LAS PALMAS TAILINGS DAM, CHILE

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ABSTRACT: This study analyzes the effectiveness of three empirical methods for estimating run-out distance of dam break analysis in the event of tailings dam failures. The case study considered is the Las Palmas tailings dam, which collapsed during the 2010 Maule earthquake. This failure released 231,660 m³ of tailings, affecting 12.5 hectares and resulting in four fatalities. The methods evaluated were those of Lucia et al. (1981), Jeyapalan et al. (1981), and Rico et al. (2008). The Lucia et al. method showed percentage errors of up to 495% in the southern direction of displacement, limited to slopes less than 4°. The Jeyapalan et al. method presented errors ranging from 1% to 30% in the southern direction of displacement, incorporating rheological variables such as viscosity (2–4 kPa·s) and yield stress (5–7.5 kPa). The Rico et al. method exhibited extreme errors, with discrepancies exceeding 1,000%, due to its reliance on historical data and simplifications. The results indicate that while empirical methods are useful for initial estimates of run-out distance, their accuracy decreases in complex scenarios such as Las Palmas. It is concluded that these methods must be complemented with dynamic simulations of dam break analysis that consider specific topographic and rheological variables to enhance community safety and minimize environmental risks in tailings storage facilities.

KEYWORDS: tailings dams; dam break analysis, run-out distance; empirical methods.

1 I INTRODUCTION

The mining industry is one of the most important economic activities at the national level [1]. This industry attracts foreign investment and stands as one of the main economic activities in several developing countries, generating significant income and employment [2]. In Chile, mining activity is responsible for directly generating 20% of the GDP (Gross Domestic Product) [1].

Currently, Chile has one of the largest copper reserves in the world [3], with approximately 5.3 million metric tons (Mt) by 2023 [4], so proper management of tailings deposits is essential [5]. Tailings production in Chile is on track to double by 2035 [6]. Currently, the volume of tailings generated in the country in 36 hours is comparable to the size of the Santa Lucía hill - located in the commune of Santiago, Chile and where its mass is estimated to be approximately 3,183,872.1 tons, however, in 20 years it is expected that this same volume will be reached in just 21 hours [6]. This means that the production rate will increase dramatically. Mining companies, as part of their mineral exploitation processes, generate large amounts of waste, which are commonly deposited in structures known as tailings dams. These deposits can pose a significant risk to communities and the environment, especially if poorly managed [7]. Worldwide, it is estimated that there are more than 15,000 tailings dams, many of which have been identified as potentially hazardous due to their age, geographic location, structural deficiencies or construction methods [8], [9]. Of the total material extracted from a mine or deposit, only 2% corresponds to the desired metal, with the remainder being waste material and consisting of waste material (50%), tailings (44%) and slag (4%) [10].

Chile is one of the countries with the highest mining activity, being a leader in the production of copper and other minerals [1]. This activity has led to the existence of more than 795 tailings dams distributed throughout the national territory, where only 16% are active, while a considerable number are inactive or abandoned, which increases the risk of structural failures [11]. One of the risks is the dangerous distances traveled by the tailings deposited in the basin after a potential failure or collapse of a dam [12]. The dangerous distance part of dam break analysis is an essential tool to manage risks and ensure that mining operations are sustainable and safe for people and the environment. The evaluation of this variable can be carried out through different methods, either empirical or through numerical modeling in software such as FLO2D, HEC-RAS, ANSYS Fluent and Flow3D.

This study analyses the run-out distance by tailings using three empirical methods: Lucia et al (1981), Jeyapalan et al. (1981) and Rico et al. (2008), using the Las Palmas tailings dam failure as a case study. These empirical methods were considered due to their simplicity and ease of use, as the input data such as dam height, terrain slope, and tailings volume are easy to obtain. Furthermore, these methods have been used in numerous studies and projects worldwide, which have contributed to their recognition and validation [13], [14], [15].

The results show that the methods used allow for obtaining a reasonable estimate of run-out distances, contributing to the assessment of risks in similar contexts. However, these methods have limitations associated with the simplification of geotechnical and topographic parameters, as well as their dependence on empirical data previously obtained in other geographic and climatic conditions.

The scope of this research focuses on the validation and comparison of empirical methods for the prediction of run-out distances, seeking to establish their applicability in the context of tailings storage facilities. However, the limitations inherent to these methods highlight the need to combine empirical approaches with advanced numerical modeling to obtain more robust predictions in scenarios of high geotechnical complexity.

This will allow for improved risk assessment, ensure the safety of nearby communities, and minimize environmental impacts on the mining industry. This highlights the need for an integrated approach that combines the simplicity and accessibility of these models with the accuracy and adaptability of dynamic simulations. Such an approach would not only contribute to improving the safety of nearby communities but would also provide a more robust framework for risk management in regions of high environmental and geotechnical vulnerability.

2 | LITERATURE REVIEW

Tailings storage facilities are constructed by a dam infrastructure containing the mining waste called tailings. This dam is built using a method known as “cycloning”, which is a separation and classification technique that uses hydro cyclones to divide the tailings flow into two fractions: the coarsest particles (underflow) and the finest particles (overflow) [16]. This process is used to build the dam more efficiently and stably. These dams can be built with the coarsest fraction of the tailings [12]. In Chile, the dam construction methods in tailings storage facilities are essential for the stability and safety of these structures and have been adapted to respond to the high seismicity of the country and the variability in the characteristics of the tailing storage facilities [17]. The most common construction methods include the downstream method and the central axis method, with the upstream construction method being the least applicable due to the higher risks associated in seismic zones [18]. In 1970, the upstream construction method was banned in Chile due to the 1965 earthquake that revealed the high susceptibility of tailings dams built upstream to liquefaction phenomena in seismic zones [19]. Supreme Decree No. 86 of 1970 [19] was a pioneer in regulating this construction method in Chile and sought to mitigate the risks associated with the stability and safety of tailings containment structures in the country.

In the Figure 1, adapted from [20], the downstream construction method, shown in Figure 1 (a), is the permitted method in Chile to build tailings dams in areas of high seismicity. Expanding the dam base in each construction phase offers greater structural stability. This approach is common in large-scale projects, where safety is prioritized and the initial investment is justified. The dam is built by expanding outwards in each phase, resting on the base of the original dam [21].

The centerline construction method, seen in Figure 1 (b), is considered an intermediate alternative and is used in projects where a balance between costs and safety is sought. This method allows effective control over the growth of the dam, both downstream and upstream, depending on the characteristics of the terrain and the type of tailings. This method also reduces the amount of construction material compared to the downstream method and is used in areas with moderate seismic activity [18].

Finally, we have the upstream construction method, which can be seen in Figure 1 (c). This has been historically used in Chile due to its low cost and speed; the upstream method was banned in 1970 [19]. In this method, the dams are built over the already settled tailings deposit, advancing towards the body of the reservoir. Although it is cheaper and requires less material, it is more susceptible to stability and liquefaction problems in case of earthquakes, especially if the tailings have not been fully consolidated. For this reason, this method is mainly used in areas with low seismicity and requires constant monitoring of the deposit conditions [13], [18], [22].

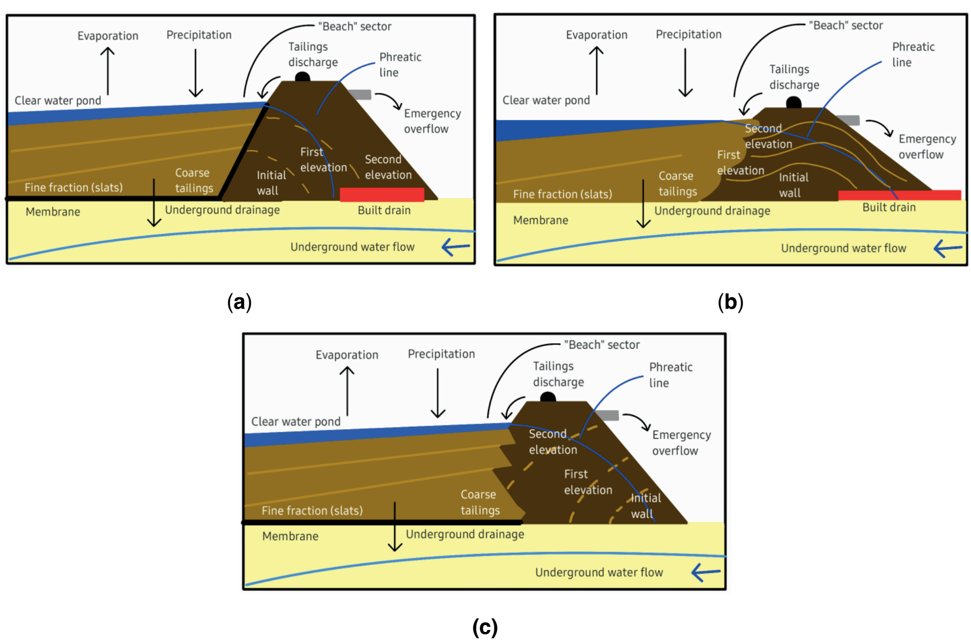


Figure 1. Construction methods for tailings dams: (a) Downstream construction method; (b) Central axis construction method; (c) Upstream construction method.

Understanding the failure mechanisms in tailings dams allows for the assessment and management of risks associated with the stability of these structures, which is essential to prevent environmental disasters and protect nearby communities. Failure mechanisms include: (i) static liquefaction, which occurs when saturated tailings suddenly lose strength, which is especially dangerous in seismic zones [23]; (ii) overtopping caused by excess water in the reservoir, which can erode the dam [24]; (iii) internal seepage and erosion or piping in the dam that creates tunnels inside the structure and weakens its stability [25] and (iv) slope sliding, when the slope or material does not offer sufficient cohesion, which causes landslides [18] (See Figure 2, adapted from [18]).

These mechanisms, such as liquefaction, overflow and slope sliding, are high risk factors in areas with high seismicity and intense rainfall, as is the case in Chile. Understanding how and why these failures occur also helps in the design of appropriate mitigation measures, from drainage and saturation control to dam slope optimization and structural reinforcements. Furthermore, knowledge of these factors is essential to comply with international and local regulations, promoting safer and more sustainable construction practices that minimize environmental impact and human safety risks [16].

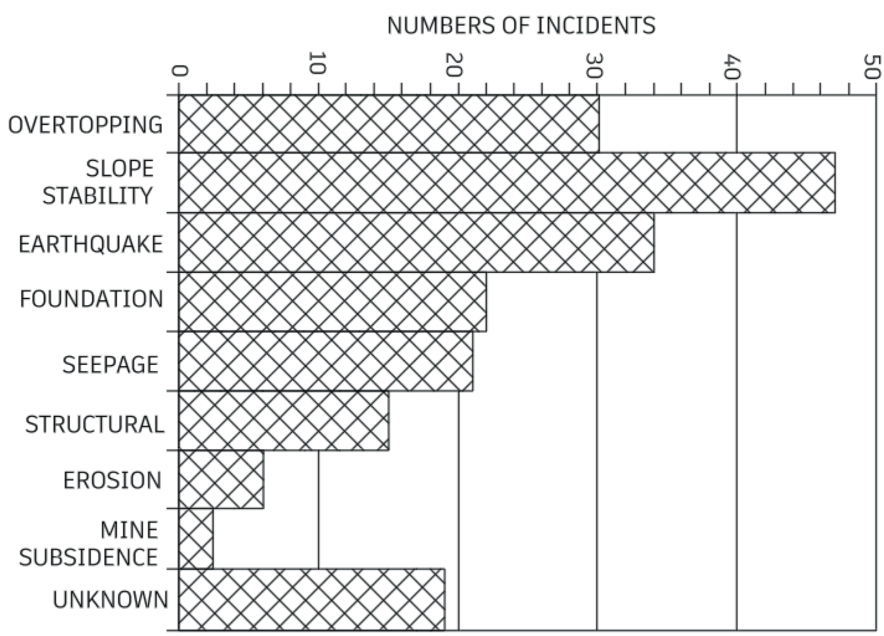


Figure 2. Most frequent failure mechanisms in tailings dams worldwide.

To estimate the run-out distance of a dam break analysis, there are empirical methods and numerical modeling [26]. The empirical methods used in this research are the following:

Method	Year	Main Characteristics	Key Parameters	Type of Analysis	Limitations
Lucia, Duncan y Seed	1981	It has a geotechnical approach considering shear resistance and slope material.	Dam height, soil shear strength, terrain slope and total stored volume.	Pseudostatic and empirical	Limited to specific seismic conditions and technical materials
Jeyapalan, Duncan y Seed	1981	Simplified model based on potential energy and projected flow in case of failure.	Tailings density, dam height, dam distance, ground slope, yield stress and tailings viscosity	Static, based in energy	It does not consider variations in flow or consideration of the environment
Rico, Benito y Díez-Herrero	2008	Based on historical events and statistical analysis of tailings dam failure.	Dam height and volume released	Statistical and empirical	Dependency on previous events, difficult to apply to new deposits without historical events

Tabla 1. Summary of the three empirical methods under study

Rico, Benito, and Díez-Herrero's research [13] is based mainly on correlations obtained after analyzing the case studies. Among them, there are correlations that consider a regression equation for the height of the dam, the volume released, and a dam factor that considers the height of the dam and the volume released (see Table 2 and Figure 3).

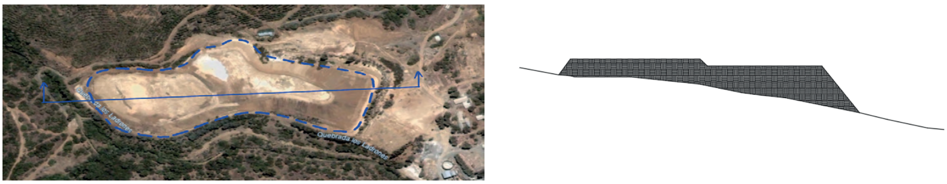
Method	Formula
Run-out Distance – Height Correlation	(1) D_{max}[1]$=0.05 \text{ x } H^{1.41}$[2], r^2[3]$=0,16$ (2) $D_{max}=0.01 \text{ x } H^{3.23}$
Run-out Distance – Volume Released Correlation	(3) $D_{max}=14.45 \text{ x } V_f^{0.76}$[4], $r^2=0,56$ (4) $D_{max}=112.61 \text{ x } V_f^{0.81}$
Run-out Distance – Dam Factor Correlation	(5) $D_{max}=1.61 \text{ x } (H \text{ x } V_f^{0.66})$, $r^2=0,57$ (6) $D_{max}=12.46 \text{ x } (H \text{ x } V_f^{0.79})$

[1] maximum run-out distance (in kilometers) the tailings travel in case of failure, [2] dam height (in meters), [3] regression equation fit and [4] total released volume (in millions of m3).

Table 2. Summary of the formulas used by Rico, Benito and Díez-Herrero.

The Las Palmas tailings dam was built on a slope to the southeast of the mining plant and underwent four growth stages between 1981 and 1998. The growth stages employed both upstream and centerline construction methods, using the coarse fraction of the tailings (cyclone tailings sands) to form the dam [27]. Figure 4, adapted from [28] and Google Maps, shows the tailings dam just before the failure, and in Figure 5, adapted from Google Maps, shows the geometry of the dam before and after the failure. The failure of the dam caused by the 27 February 2010 Chile earthquake generated a tailings flow that traveled approximately 350 meters south and 165 meters east, releasing a volume of 231,660 m³ of material, as can be seen in Figure 5 (b). This flow resulted in severe damage, affecting

12.5 hectares of land and causing the deaths of four people living nearby [27]. The material used for the construction of the dam showed that it was built with low quality materials, the compaction of the dam was not sufficient, and a high saturation was detected at the base of the dam after the applied tests [29], [30].



(a) (**b**)

Figure 4. The geometry of the tailings dam just before the failure: (a) Geometry of the dam before the failure (2005); (b) Geometry of the dam before the failure (section).

Before the closure of its operations in 1997, the tailings storage facility had a dam height of around 28 meters. Investigations carried out after the failure pointed to several contributing factors, such as the poor geotechnical characteristics of the material used in the dam and saturation at the base of the dam. It was concluded that these problems facilitated the liquefaction of the material during the seismic event, leading to the collapse of the dam [31], [32].

Following the disaster, SCM Tambillos, the responsible mining company, was convicted of environmental damage [33]. The ruling ordered the implementation of an Environmental Repair Program (PRA), including measures to ensure the stability of the dam and reduce future environmental and health risks. Among the planned actions are the control of runoff, waterproofing of the dam and the collection of contaminated soil [33].

(a) (**b**)

Figure 5. Geometry of the Las Palmas tailings dam: (a) Geometry of the dam before the failure (2005); (b) Geometry of the dam after the failure (2010).

3 I METHODOLOGY

This research focused on the Las Palmas tailings dam in Chile to estimate run-out distances using three empirical methods. The methods of Lucía et al. (1981), Rico et al.

(2007) and Jeyapalan (1981) employ key modifiable variables to adjust their models for assessing run-out distances in tailings dams, adapting to different structural and geographic conditions. In the Lucía et al. method, dam height, tailings volume, ground slope, and material type can be modified to simulate different stability and material projection scenarios in case of failure.

Rico et al. propose modifying tailings volume and dam height to predict the extent of a possible tailings flood based on ground slope and roughness. Jeyapalan, on the other hand, focuses on variables such as the slope of the downstream terrain, the geometry of the dam, the height of the dam, and the rheological properties of the material, allowing the evaluation of the structural stability of the dam under seismic loads and liquefaction susceptibility. Together, modifying these variables enables the customization of empirical models to reflect specific conditions of each tailings dam, achieving a more accurate prediction of the extent and risk of a possible collapse.

The Las Palmas tailings dam was selected because the failure of this dam occurred over 14 years ago, so it has advanced monitoring. After the failure, the geotechnical and environmental conditions caused by the dam failure were monitored [34]. The monitored data are accessible because this dam has been widely studied, which has led to several exhaustive investigations to determine the geotechnical conditions of the tailings and the dam that will be used later [28]. The geographic location is important because its location is representative for studying tailings in regions with similar characteristics (semi-arid climate zone, soils and topography). In addition, in the vicinity of the Las Palmas Tailings Dam there are communities and infrastructure that require risk assessment. Additionally, this tailings dam was considered because it was in an “abandoned” state when the dam failure occurred, thus, this study seeks to emphasize the work of supervising tailings dams in this condition to avoid future catastrophes, given that the objective of this study is to compare the efficiency of different empirical approaches and maximize rigor in this same analysis.

The methodological approach is presented in Figure 6 and illustrates the methodological process used to carry out a systematic and bibliometric review aimed at analyzing failures in tailings dams. Initially, two systematic searches were carried out using specific keywords: “dam break analysis” and “dam break and tailings.” These searches resulted in the identification of 21 documents, of which 5 were discarded after a relevance review. In parallel, additional references provided by professors and engineering experts were integrated, complementing the bibliometric review with empirical methods and national and international regulations associated with the functioning, operation and closure of tailings dams.

Finally, among the selected documents, the studies by Lucia et al. (1981), Rico et al. (2007) and Jeyapalan (1981) stand out, which were used to calculate run-out distances using empirical approaches. This combined systematic review and bibliometric approach ensures a solid information base to support geotechnical and environmental assessments associated with tailings dam failures.

This approach not only helps mitigate risks, but also contributes to developing more robust standards in tailings engineering. Implementation of these methods could be essential to ensure the safety of nearby communities and protect the environment from disasters caused by tailings dam failures.

Finally, it is possible to mention that the study method used is comparative, since it focuses on the evaluation and contrast of three empirical methods highlighted in the literature: Lucia et al. (1981), Rico et al. (2007) and Jeyapalan (1981). These approaches have been selected due to their relevance in the analysis of tailings dam failures and the recognition they have in the scientific and technical community. The comparison allows to identify similarities and differences in the parameters used and the results obtained, thus contributing to a more comprehensive understanding of the run-out distances and their relationship with the geotechnical and geomorphological characteristics of the dams analyzed.

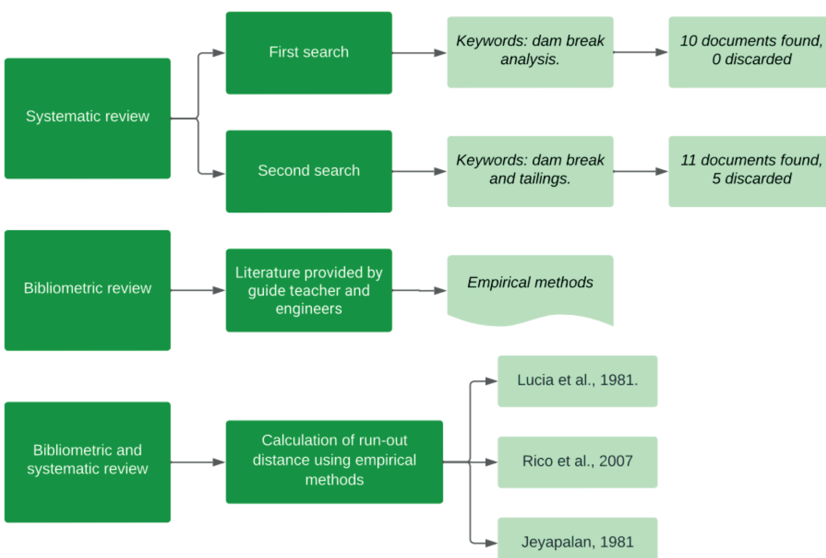


Figure 6. Diagram of methodology used to search for information and subsequent analysis.

4 I RESULTS

Based on the methodology described in Figure 6, the calculation results for the three empirical methods are presented, and a summary table with the percentage error calculation to the run-out distance measured on the ground is presented.

4.1 Lucia et al. 1981:

The model consists of intercepting the shear strength curve of the soil mass with its respective volume curve. The diagram can be seen below in Figure 7, adapted from [15]:

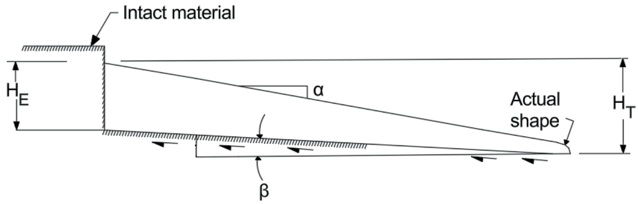


Figure 7. Idealized cross-section for estimating run-out distances.

For the calculation of run-out distances, the method proposed by the authors mentions that the total stored volume must be considered and not the released volume, because it is an estimate for when the tailings dam has not yet failed, so the following parameters shown in Table 3 are used:

Parameters	Adopted Value	Units
Tailings density (γ)	1,8	ton/m^3
Total volume before failure	410.570	m^3
Residual shear strength (Su)	0,7	ton/m^2
Terrain slope (β)	3- 4 [1]	°

[1] For this case, an analysis was carried out varying the slope of the final terrain.

Table 3. Parameters of the method proposed by Lucia, Duncan and Seed and adopted values.

For the purpose of this research, the slope of the terrain (β) was varied because it directly influences the kinetic energy of the flow and its ability to advance. As the slope increases, it is expected that the distance traveled by the flow will also increase, while lower slopes will limit its reach. Therefore, to evaluate this sensitivity, the calculation of the run-out distance will be carried out with several relevant slopes, as long as they are less than 4°, because the authors limit their method to slopes less than 4° [15]. This consideration about limiting slopes to less than 4° may underestimate the results, because low slopes are being used about the topography observed in the tailings dams, especially in the Las Palmas tailings dam.

In the following section, there will be the results for the effects of both slopes analyzed, corresponding to β= 3° and β= 4°.

4.1.1 Effects of terrain slope (β= 3° and β= 4°):

First, a 3° terrain slope will be considered, assuming that the terrain conditions may be similar to those proposed in this analysis. In addition, we will consider a 3° slope because the author limits his calculation methodology to maximum slopes of 4°. To predict the run-out distance, we must intercept two curves, the resistance curve and the volume curve. After intercepting these curves, we will obtain the results for the terrain slope β= 3°, in Table 4.

	Height Ht	Repose Slope α	Run-out Distance
Case 1 (C1)	79.0	2.13	2.08 [km]
Case 2 (C2)	20.0	4.96	0.23 [km]

Table 4. Run-out distance values obtained for β= 3°

Next, we will consider a terrain slope equal to 4°. To predict the run-out distance we must intercept two curves, the resistance curve and the volume curve. After intercepting these curves, considering the slope of β= 4°, we will have the results in Table 5.

	Height Ht	Repose Slope α	Run-out Distance
Case 3 (C3)	22.6	4.74	0.25 [km]
Case 4 (C4)	10.3	7.19	0.08 [km]

Tabla 5. Run-out distance values obtained for β= 4°

Figure 8 shows the run-out distance associated with a tailings dam, considering different points of analysis such as the change in the terrain slope used (β= 3° and β= 4°) and its comparison with the distances measured after the failure in the south and east directions. The bars represent the critical run-out distances in kilometers, where significant impacts could be observed in case of a dam failure. The points C1, C2, C3, and C4 indicate strategic locations selected for the analysis, while the actual values correspond to run-out distances observed in specific directions, such as south and east.

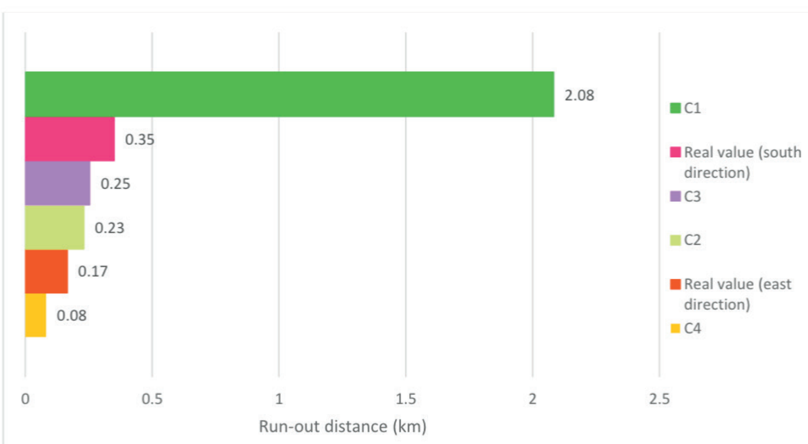


Figure 8. Results of the Lucia et al. (1981) method compared to values obtained in the field.

4.2 Jeyapalan et al. (1981):

The work of Jeyapalan, Duncan and Seed (1981) for the calculation of run-out distance is based on empirical principles that relate the physical characteristics of the structure and the volumes released to the distance that the materials will travel downstream.

The calculation of run-out distances proposed by the authors combines information such as the height of the dam wall and the rheological properties of the tailings. The parameters that apply to this method and the values used for the calculation are in Table 6.

Parameters	Adopted Values	Units
Tailings density (γ)	18	kN/m^3
Dam height	28	m
Dam distance	215	m
Terrain slope	0,07	m/m
Yield stress (τy)	5- 6- 7.5 [1]	kPa
Viscosity (μ)	2- 3- 4 [2]	kPa·s

[1,2] For this case, an analysis was carried out varying the yield stress and the viscosity of the fluid.

Tabla 6. Variables of the method proposed by Jeyapalan, Duncan and Seed and adopted values.

The author mentions that the values corresponding to the yield stress (τy) and viscosity (μ) must be within their own acceptable ranges [14], which can be found below:

1. Viscosity: Minimum, 2 lbf s/ft² (0.1 kPa). Maximum, 100 lbf s/ft² (5 kPa).
2. Yield stress: Minimum, 20 psf (1 kPa). Maximum, 150 psf (7.5 kPa).

Therefore, values in that range are used for the yield stress (τy) and viscosity (μ).

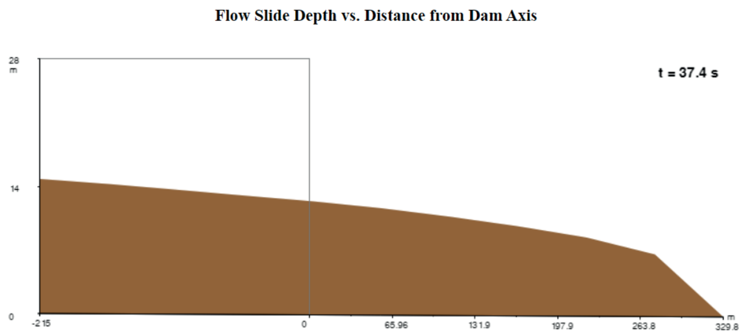
To calculate the run-out distance for the proposed method, the virtual calculator Tailings Flow Slide Calculator [35] was used. Nine calculations corresponding to each possible combination between yield stress and viscosity will be performed, and the results are shown in Table 7.

Parameters		Adopted Value		Units
Yield Stress (τy)		5		kPa
Viscosity (μ)	2	3	4	kPa·s
Run-out distance	411.4	329.8	276.8	m
Mean velocity	9.2	8.8	6.7	m/s
Yield Stress (τy)		6		kPa
Viscosity (μ)	2	3	4	kPa·s
Run-out distance	383.4	310.5	260.6	m
Mean velocity	9.2	9.2	8.6	m/s
Yield Stress (τy)		7.5		kPa
Viscosity (μ)	2	3	4	kPa·s

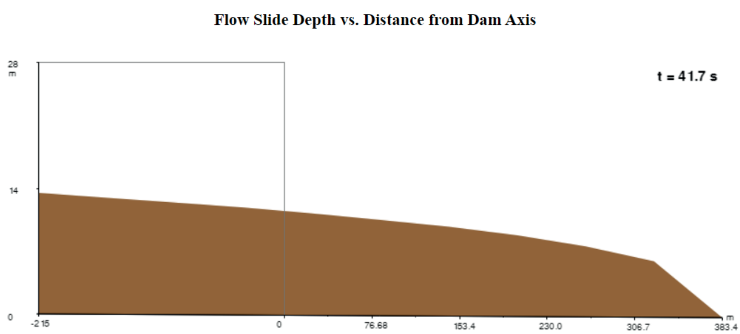
Run-out distance	344.8	283.7	244.0	m
Mean velocity	9.5	9.5	9.2	m/s

Table 7. Results for an adopted yield stress and viscosity.

The graphic results that the calculator gives us can be found in figure 9, adapted from [35]:



(a)



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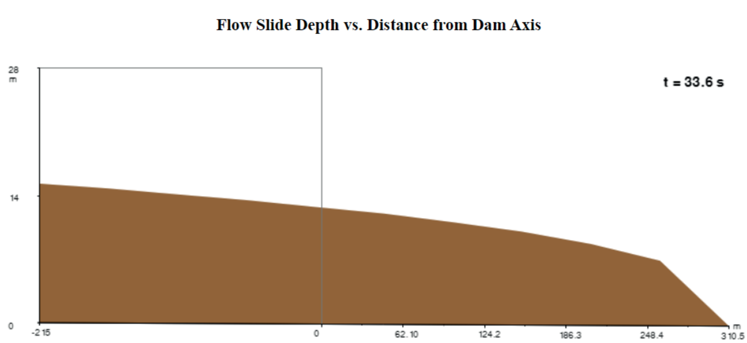

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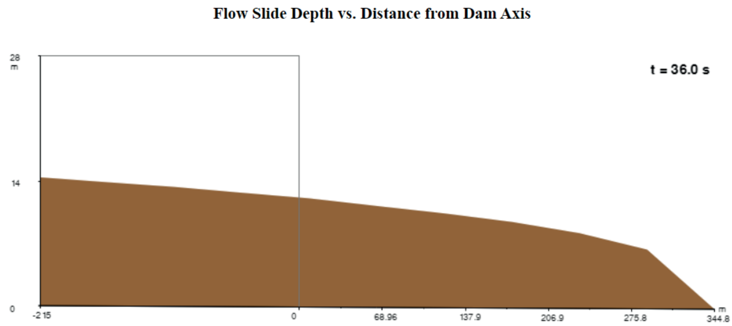

(**d**)

Figure 9. Run-out distance obtained for the Jeyapalan, Duncan and Seed method: (a) Run-out distance: τy= 5 [kPa] and μ= 3 [kPa·s]; (b) Run-out distance: τy= 6 [kPa] and μ= 2 [kPa·s]; (c) Run-out distance: τy= 6 [kPa] and μ= 3 [kPa·s]; (d) Run-out distance: τy= 7.5 [kPa] and μ= 2 [kPa·s].

Figure 10 shows the run-out distance in meters, calculated under different yield stress (τy) and viscosity (μ) conditions, to assess the material flow behavior during a tailings dam failure. The bars represent the results for specific parameter combinations (τy and μ) and the actual observed flow values in the south and east directions.

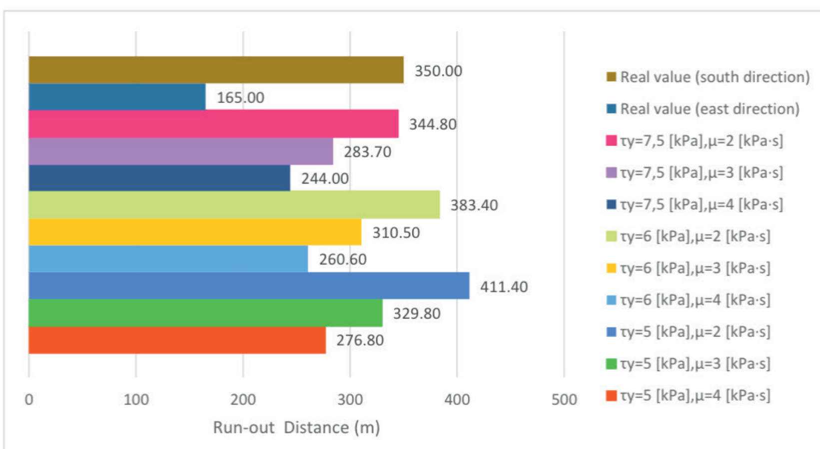

Figure 10. Results by the Jeyapalan method.

4.3 Rico et al. (2008):

The methodology of Rico, Benito and Díez-Herrero [13] focuses mainly on establishing correlations derived from the analysis of the case studies. The equations were defined in Table 2 and the applied variables are the height of the dam equal to 28 m and the released volume, which corresponds to 231,600 m3.

Equation	Value	Units
Correlation Run-out Distance – Dam Height		
(1)	5.5	Km
(2)	472.4	Km
Correlation Run-out Distance – Volume released		
(3)	4.8	Km
(4)	34.4	Km
Correlation Height – Volume (Dam factor)		
(5)	5.5	Km
(6)	54.6	Km

Table 8. Results obtained using the method of Rico et al., (2008).

4.3.1 Run-out distances obtained using the Rico, Benito and Díez-Herrero method:

The results obtained by Rico et al. are presented in Figure 11 and focus on the analysis of the behaviour of tailings dam failures in different regions of the world, considering factors such as the volume of material released and the height of the dam.

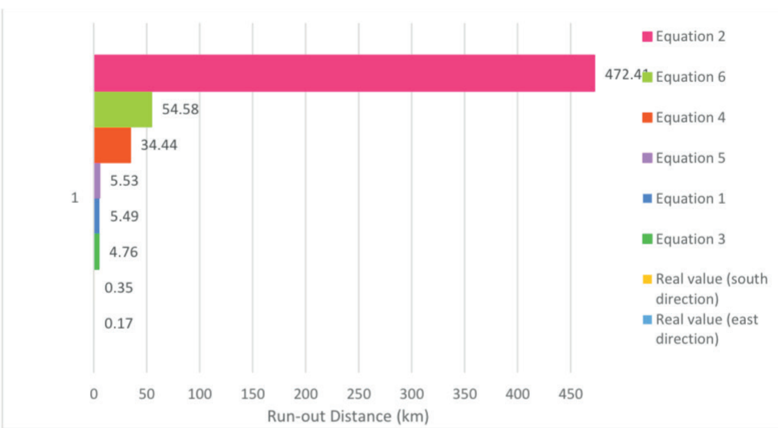

Figure 11. Run-out distances obtained using the Rico, Benito and Díez-Herrero method.

4.4 Percentage error of the results considering the real values

Table 9 presents a summary of the percentage errors obtained when evaluating different empirical methods in the south (350 meters) and east (165 meters) directions. Values are analyzed for selected variables, including inclination angles β, specific figures, and proposed equations. Errors vary considerably between methods, showing significant discrepancies that reflect the sensitivity of the models to the conditions evaluated.

Method	Parameters/Figure	Error south direction (350 meters)		Error east direction (165 meters)	
Lucia, Duncan y Seed	β=3°	495%[1]	34%[2]	1162%[1]	54%[2]
	β=4°	27%[3]	77%[4]	54%[3]	51%[4]
Jeyapalan, Duncan y Seed	τy= 5 [kPa] μ= 2 [kPa·s]	18%		149%	
	τy= 5 [kPa] μ= 3 [kPa·s]	6%		100%	
	τy= 5 [kPa] μ= 4 [kPa·s]	21%		68%	
	τy= 6 [kPa] μ= 2 [kPa·s]	10%		132%	
	τy= 6 [kPa] μ= 3 [kPa·s]	11%		88%	
	τy= 6 [kPa] μ= 4 [kPa·s]	26%		58%	
	τy= 7,5 [kPa] μ= 2 [kPa·s]	1%		109%	
	τy= 7,5 [kPa] μ= 3 [kPa·s]	19%		72%	
	τy= 7,5 [kPa] μ= 4 [kPa·s]	30%		48%	
Rico, Benito y Díez-Herrero.	Equation 1	1,468%		3,226%	
	Equation 2	134,875%		286,210%	
	Equation 3	1,259%		2,782%	
	Equation 4	9,741%		20,775%	
	Equation 5	1,480%		3,252%	
	Equation 6	15,493%		32,977%	

[1]C1. [2]C2. [3]C3.[4]C4.

Table 9. Summary of percentage errors calculated for each empirical method

Figure 12 presents graphs of the percentage errors calculated for the Lucia, Duncan and Seed methods, and the Jeyapalan, Duncan and Seed methods. These graphs allow for a comparison of the relative accuracy of each model in the context of the Las Palmas tailings dam. It is worth noting that the error associated with the Rico, Benito and Díez-Herrero method was not included due to its high percentage of error, which makes it difficult to visualize the results in the same range effectively. This graphical representation facilitates comparative evaluation and highlights the areas of potential improvement for the models analyzed.

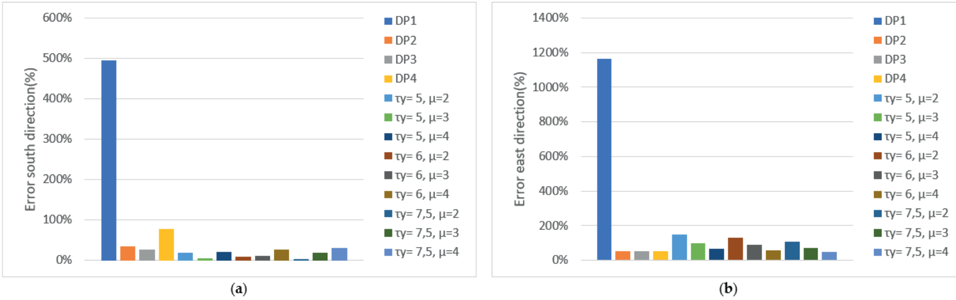

Figure 12. Graphs of previously calculated errors for the Lucia, Duncan and Seed, and Jeyapalan, Duncan and Seed methods: (a) Percentage error for the south direction (350 meters); (b) Percentage error for the east direction (165 meters).

5 I DISCUSSION

The dams of the tailings storage facilities are built (mostly) by the coarse fraction of the tailings, due to its high permeability and resistance, which helps to improve the stability of the dam reducing the risk of liquefaction during seismic events [36]. This dam mixes two construction methods, which are upstream and construction in the central axis. Due to the applied regulations in Chile, Supreme Decree No. 86 of 1970 [19], it is concluded that this tailings dam does not comply with the regulations regarding the construction method of the tailings dam, because an upstream construction method was used. In addition, it can be inferred that the level of compaction of the dams was not ideal, because it has been pointed out as a critical factor in its collapse during the Maule earthquake in 2010 [29], [30].

Rheological parameters affect the tailings flow condition, but the values used for the analysis can be estimated to be within the acceptable range indicated in section 4.2. of this study [14]. On the other hand, the analyzed methods present significant limitations when applied to the case of the Las Palmas tailings dam. One of the main limitations lies in the dependence on historical data, which may not accurately represent the current configuration of this structure, especially in a context of dynamic changes in topography or physical and chemical properties of the material. This approach generates models that simplify both the shape and composition of the dam, limiting the ability of the results to capture the real complexities. These simplifications can be problematic when evaluating critical scenarios, such as seismic events or intense rainfall, that alter the operational conditions of the tailings storage facility.

In the case of the Lucia et al. (1981) method, the results showed that it is capable of estimating run-out distances with an error of 27% to 495% in the [m-south] direction of the tailings displacement and an error of 51% to 1162% in the [m-east] direction. This method, which is based on the residual shear strength and the total volume stored in the dam, proved to be useful for situations where the geotechnical parameters are clearly defined. However, its main limitation lies in the restriction of its application to slopes less than 4°. This simplification excludes scenarios where the tailings flow may be driven by steeper slopes, which may lead to an underestimation of the risk. In regions such as Chile, with highly variable topography, this restriction underlines the need for a more adaptive and dynamic analysis. On the other hand, this method is conservative, since the authors mention that the worst flow conditions must be assumed - for example, that in the event of a failure, all the stored material will flow and thus a safety margin is guaranteed.

The method of Jeyapalan et al. (1981) [14] stands out by including rheological variables such as yield stress and tailings viscosity [37], which allow the flow behavior to be modeled in greater detail. This approach is particularly valuable in scenarios where material dynamics play a crucial role, such as in highly saturated tailings or in cases of liquefaction. However, its dependence on these parameters introduces a major vulnerability: its accuracy is affected when material properties are heterogeneous or change significantly over time [38]. Furthermore, although its flow modeling offers greater accuracy than the Lucia method in certain contexts, its application remains limited in complex terrain or in cases of extreme events, such as torrential rains or high-intensity earthquakes [39].

The Rico et al. 2008 method combines empirical and theoretical models, which often use historical accident data to derive formulas. In addition, this method considers many relationships concerning the released volume, which would not be useful in estimating a possible run-out distance, since the released volume can only be known post-failure. This method showed the largest discrepancies with the actual observed values. By relying on historical data and general correlations, this approach tends to be less accurate in contexts such as Las Palmas tailings dam, where the specific conditions of the reservoir and the geographic environment do not closely match the past events used to build the model. Although its simplicity makes it accessible for initial assessments, its applicability is limited in novel scenarios or in reservoir configurations not represented in the available historical data. This was evidenced by the high percentage of errors reported, making it less reliable for detailed risk studies.

Overall, all three methods share common limitations that affect their practical utility. They all assume average or simplified ground and tailings flow conditions, ignoring key dynamic factors such as pore pressure generation, solid-liquid interactions, or abrupt changes in downstream topography. Furthermore, the methods do not fully incorporate the effects of extreme events such as heavy rainfall or seismic shaking, limiting their ability to predict run-out distances in high-risk contexts. This lack of dynamic integration underscores the importance of complementing empirical methods with advanced numerical analysis and simulations that more accurately reflect local conditions and material interactions [40].

6 I CONCLUSIONS

This study provided a comparative analysis of three empirical methods—Lucia et al. (1981), Jeyapalan et al. (1981), and Rico et al. (2008)—applied to the calculation of run-ou distances in the context of tailings dam failures. The results obtained demonstrate that the empirical methods analyzed present variable levels of accuracy and utility, which are directly influenced by the characteristics of the dam and the surrounding conditions. Factors such as the terrain's slope, the dam's height, and the volume of tailings released play a fundamental role in the capacity of the methods to adapt to a specific scenario. For example, the method of Lucia et al. (1981) is favored in terrains with slopes less than 4°, where the residual shear strength and the total volume stored are the dominant variables that determine its accuracy.

On the other hand, the method of Jeyapalan et al. (1981) incorporates rheological variables such as viscosity and yield stress of the tailings, allowing for greater sensitivity to the dynamic properties of the flow. This results in better fit-in scenarios where the behavior of the released material depends on these characteristics. However, its accuracy decreases in cases where these variables are not well-defined or vary significantly.

The Rico et al. (2008) method, although simpler, relies on historical correlations that assume fixed relationships between dam height, volume released, and distance traveled. This approach is less adaptable to new configurations or environments with significant variability, such as the Las Palmas tailings dam. Here, the specific topography, material distribution, and interaction between the tailings flow and downstream terrain are factors that the method does not adequately address.

In addition to the points already discussed, this study allows us to draw conclusions that highlight both their importance and their relevance for risk management and prevention in tailings dams. A crucial conclusion is that the comparison of empirical methods highlights the need to adapt risk assessment tools to the specific conditions of each dam. This is particularly relevant in regions such as Chile, where high seismicity, steep slopes and increased tailings generation add complexity to the safety analysis of these structures.

The study also shows that while empirical methods are useful for providing initial estimates, their limitations highlight the importance of integrating more advanced approaches, such as numerical simulations and dynamic analysis. These tools can capture phenomena such as liquefaction, pore pressure generation, and flow-ground interaction, which are not considered in empirical models. This analysis underlines the urgency of implementing hybrid approaches that combine the best of both worlds: the simplicity of these methods and the accuracy of detailed simulations.

This analysis provides a frame of reference that can be applied beyond the specific case of the Las Palmas tailings dam, since the principles studied are transferable to other mining contexts with similar challenges. This reinforces the importance of conducting ongoing research and periodic updates to the models and methods used, to ensure the safety of communities and environmental sustainability in an industry that faces increasing pressure to maintain higher safety standards.

This work contributes to engineering practice by evaluating and comparing empirical methods (Lucia et al., Rico et al., and Jeyapalan) to determine run-out distances associated with tailings dam failures. The results obtained can serve as a guide for engineers looking for preliminary assessment tools in similar contexts. In addition, it highlights the importance of considering local conditions and specific geotechnical parameters in the design and monitoring of tailings dams. However, comparative analysis contributes to the theoretical body by highlighting the limitations of empirical methods when applied outside their original contexts. It also reinforces the need to integrate empirical methods with more advanced numerical models to capture complex interactions and site-specific conditions.

Finally, a key limitation is a focus on empirical methods, which do not dynamically reflect local conditions and material interactions in real-time. Furthermore, the analysis relies on existing data, which restricts the ability to validate the methods with new observations or simulations. Research that integrates empirical methods with numerical analysis and advanced simulations is recommended. This would include the evaluation of real-time dynamic models and the use of modern sensors to capture more accurate geotechnical data. It would also be useful to explore how climatic conditions and dam design changes affect the analyzed methods' validity.

AUTHOR CONTRIBUTIONS

Conceptualization, A.M. and R.G.; methodology, R.G.; software, A.M.; validation, R.G., E.A. and C.C.; formal analysis, A.M.; investigation, A.M. and R.G.; resources, A.M.; data curation, A.M.; writing—original draft preparation, A.M. and R.G.; writing—review and editing, E.A. and C.C.; visualization, A.M.; supervision, R.G.; project administration, R.G. and E.A.; funding acquisition, E.A. and C.C. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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