XX ICongresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica
X Simpósio Brasileiro de Mecânica das Rochas
X Simpósio Brasileiro de Engenheiros Geotécnicos Jovens
24 a 27 de setembro de 2024 – Balneário Camboriú/SC

DOI: 10.47094/COBRAMSEG2024/1

A data-driven approach linking the credible failure modes for TSFs risk assessment.

Danielle Aparecida de Menezes
PhD candidate, Federal University of Ouro Preto, Ouro Preto, Brazil, danielle.menezes@aluno.ufop.edu.br

José Matheus Vieira Matos
Master candidate, Federal University of Ouro Preto, Ouro Preto, Brazil, jose.matos@aluno.ufop.edu.br

Hernani Mota de Lima
PhD Professor, Federal University of Ouro Preto, Ouro Preto, Brazil, hernani.lima@ufop.edu.br

Tatiana Barreto dos Santos
PhD Professor, Federal University of Ouro Preto, Ouro Preto, Brazil, tatiana.santos@ufop.edu.br

ABSTRACT: This study proposes a methodology to evaluate correlations between credible failure modes and risk controls for tailings storage facilities (TSFs), considering its characteristics and similarity. A dataset of 66 collapsed TSFs with known failure modes was analyzed. Variables included processed ore type, construction material and method, height, volume, seismic risk, and climate. The dataset was assessed for representativeness and to identify potential correlations for predicting structure behavior related to failure modes. Results showed that 21% of dams failing due to seismic liquefaction were in very high seismic risk zones, with 18% located in temperate climates. Upstream construction methods exhibited significant associations with static liquefaction (21%), seismic liquefaction (19%), and overtopping (12%). Regarding dam material, 15% of failures due to seismic liquefaction involved specific materials. Height and volume had minimal influence on failure modes within the analyzed dataset. These findings demonstrate the influence of structural characteristics on failure modes, enabling the correlation of applicable risk controls with TSF management and governance.

KEYWORDS: Tailings storage facility, credible failure mode, risk assessment

RESUMO: Este estudo propõe uma metodologia para avaliar correlações entre modos de falha criveis e controles de risco para instalações de disposição de rejeitos (TSFs), considerando suas características e similaridades. Um conjunto de dados de 66 TSFs colapsadas com modos de falha conhecidos foi analisado. As variáveis incluíram tipo de minério processado, material e método de construção, altura, volume, risco sísmico e clima. O conjunto de dados foi avaliado quanto à sua representatividade e para identificar correlações potenciais e prever o comportamento da estrutura relacionado aos modos de falha. Os resultados mostraram que 21% das barragens que falharam devido à liquefação sísmica estavam em zonas de risco sísmico muito alto, com 18% localizadas em climas temperados. Os métodos de construção a montante exibiram associações significativas com liquefação estática (21%), liquefação sísmica (19%) e transbordamento (12%). Em relação ao material da barragem, 15% das falhas devido à liquefação sísmica envolveram materiais específicos. Altura e volume tiveram influência mínima nos modos de falha dentro do conjunto de dados analisado. Esses achados demonstram a influência das características estruturais nos modos de falha, possibilitando a correlação de controles de risco aplicáveis com a gestão e governança de TSFs.

PALAVRAS-CHAVE: Estrutura de disposição de rejeitos, modo de falha crível, análise de risco

1 INTRODUCTION

Risk assessment plays a critical role in tailings management, as it directly influences the understanding of potential failure mechanisms in Tailings Storage Facilities (TSFs). As stated by ICMM (2021a), the primary goal of a TSF risk analysis is to identify potential failure modes. This allows for the implementation of appropriate risk management measures to reduce the likelihood of failure and/or mitigate its consequences.

Huang et al. (2020) define failure modes analysis as a systematic method for identifying how a system (or its components) might fail, along with the associated causes. Liquefaction (both static and seismic), structural failure, piping, and overtopping are among the most common failure modes for TSFs.

The Global Tailings Review (GTR, 2020) introduces the concept of credible failure modes. These are potential failure mechanisms that can arise from various factors throughout a TSF's lifecycle, including foundation materials, structural properties, slope design, drainage, and water management practices. The GTR acknowledges that credible failure modes can change as conditions at the facility evolve.

While different failure modes can lead to distinct failure scenarios, it's important to understand that labeling a failure mode as "credible" doesn't necessarily indicate its likelihood of occurring or the overall safety of the TSF. Instead, a credible failure mode signifies a mechanism that has the potential to cause a TSF failure.

1.1 Credible failure mode

Accurately identifying failure modes is crucial for pinpointing controls that can reduce the likelihood of failure occurrence. ICMM (2021a) defines a credible failure mode as one where the associated mechanism triggers an event that leads to the resulting failure.

TSFs face several common failure modes, as outlined below:

- **Liquefaction:** As highlighted by Robertson and Fear (2017), liquefaction is a significant concern for TSFs built on sandy soils. This phenomenon involves a sudden strength loss in loose sands, causing them to flow like a slurry when disturbed. It can be triggered by applied stress, a rapid change in stress conditions (static liquefaction), or earthquakes (seismic liquefaction). The Fundão Dam failure (Brazil, 2015) and the Brumadinho Dam failure (Brazil, 2019) are examples of such failures. Both these upstream method (CSP 2) facilities utilized sandy soils.
- **Structural failure:** This occurs due to weaknesses in the TSF itself, its foundation, or its abutments. ICMM (2021a) mentions factors like brittle materials or excessive settlement in soft zones as potential causes. This failure mode is more common in facilities with poor foundation permeability, leading to increased pore pressure and reduced strength. The Mount Polley failure (Canada, 2014) is a case of structural failure due to a foundation fault. This centerline method (CSP 2) dam experienced such a failure.
- **Piping:** ICOLD (2017) defines piping as the erosion of internal soil particles within a dam or its foundation due to seepage flow. This failure mode often occurs during initial filling as weaknesses are exposed by rising water levels. ICMM (2021a) emphasizes the importance of considering both physical and chemical aspects of TSFs throughout their lifecycle to prevent piping failures. As an example, in 2010, the Ajka Alumina Dam constructed using the downstream method failure by piping in Hungary (CSP 2).
- **Overtopping:** This typically results from extreme storms or landslides within the impoundment. ICMM (2021a) stresses the importance of adequate freeboard and considering all design, construction, operation water management, and closure criteria uncertainties to ensure safety against overtopping failure. The Merriespruit Dam in South Africa, built in 1978, experienced a breach in its dam wall following heavy rain in 1994 (CSP 2).

Risk controls for these failure modes need to be tailored to each specific scenario, considering various conditions that indicate potential failure. This research aims to support the identification of credible failure modes as a reference for establishing minimum and specific risk controls required for each mode, considering key structural characteristics and the Tailings Governance Structure.

To understand dam failure and enhance the understanding of the relationship between TSF characteristics and failure modes, various databases were consulted, as described in the following section.

1.2 Tailings Dataset

Analysis of tailings dam (TSF) failure data from databases like ICOLD, WISE, and CSP 2 confirms dam failure as a credible failure mode. This research aims to identify characteristic differences between failed and non-failed TSFs recorded in these databases. This will help establish representative features to improve the understanding of TSF risks and inform the implementation of appropriate risk controls for enhanced safety. Several databases were consulted for this study:

- **WISE:** Established in 1961, WISE provides detailed incident reports for 157 tailings dam failures. It includes information on ore type, incident type, tailings release, and associated impacts. However, WISE lacks in-depth data on failed dam characteristics and is not optimized for statistical analysis.
- **ICOLD Bulletin 99 (2019):** This update by ICOLD offers a valuable approach using statistical analysis of dam failures. However, the database includes not only TSFs but also other dam types, encompassing 322 failure cases from 1884 to 2018. For this research, the relevant aspects are the incident context and registered failure modes (foundation failure (17%), internal erosion (25%), overtopping (24%), structural failure (27%), and unknown (7%)).
- **CSP 2:** This database is a comprehensive record of tailings dam failures globally, with 368 cases documented from 1915 to 2022. It includes dam failures resulting in over 3,241 fatalities and the release of more than 250 million cubic meters of contaminated material downstream. Notably, CSP 2 data indicates a significant increase in failures after 2000 (113 dams).

The Matos (2023) database was ultimately chosen for this research due to data quality concerns in other sources. Matos (2023) rigorously treated data from the CSP database, addressing issues of incomplete information and missing data for many dams. This resulted in a focused dataset of 66 tailings dams.

The Matos (2023) database includes the following information for each TSF: type of ore processed, dam construction material and method, dam height, stored tailings volume, and failure mode. Additionally, Matos (2023) incorporated two crucial variables: seismic risk level (classified as very low to very high) and prevailing climate conditions (based on the widely used Koppen classification system). Seismic risk data was obtained from the Socioeconomic Data and Applications Center (SEDAC), a NASA resource, while climate data was categorized according to the Koppen classification, as outlined by Rolim et al. (2007).

1.3 Risk Controls

ICMM (2021a) defines risk controls as a series of measures implemented to either prevent unwanted events (like dam failures) from occurring or to minimize their negative consequences if they do happen. Critical controls, as per ICMM (2021a), are those essential for preventing undesirable events or significantly reducing their impact. Even with other controls in place, the absence or failure of critical controls can dramatically increase the risk.

The effectiveness of implemented controls significantly influences whether a credible failure mode translates into a catastrophic failure. ICMM (2021a) associates catastrophic failure with flow failures, which lead to severe consequences upon occurrence.

Silva (2020) emphasizes, using examples like Fundão and Brumadinho dam failures, that conventional TSF failures can have far-reaching spatial, temporal, and territorial consequences that are not easily resolved. Given the severity of impacts, the problem's complexity, and potential conflicts arising from dam and disaster risks, geographical and socio-environmental studies offer a valuable opportunity for interdisciplinary exploration.

Credible failures can differ significantly between conventional dam-like TSFs and non-conventional TSFs, as shown by Machado (2017) and Almeida et al. (2021). Retro analyses of the Fundão Dam failure by these researchers revealed discrepancies in peak flow results due to differing breach widths used in each analysis. However, they reached agreement on the wave propagation distance and maximum wave height.

Silva and Meguet (2021) investigated credible failure scenarios for a "Stack Break" facility, simulating a complete collapse. They observed limited potential for mobilized material movement after the initial rupture. This resulted in the rapid filling of the downstream valley, followed by a quick stop in a new stable configuration. This case study provides valuable insights for developing appropriate Emergency Preparedness and Response Plans (EPRPs) that consider the magnitude of potential impact scenarios.

Identifying credible failure modes for a Tailings Storage Facility (TSF) is crucial. This allows for the selection of appropriate controls to mitigate failure risks during tailings management and the establishment of governance practices aligned with the company's organizational structure.

2 METHODOLOGY

This section outlines the methodology used to identify credible failure modes for a tailings storage facility (TSF) database using the approach proposed by Matos (2023). The analysis aims to assess the effectiveness of implemented risk controls in tailings management and governance.

2.1 Data Collection and Processing

The first step involved gathering data on 28 TSFs, including ore type, dam construction materials and methods, height, volume, seismic risk, climate, and any recorded failure modes. This data was used to identify credible failure modes for each TSF following Matos' methodology.

The collected data was then cleaned and preprocessed to remove inconsistencies, handle missing values, and normalize features for further analysis. This ensures the data is suitable for modeling techniques like machine learning or statistical models used to predict failure modes based on available data.

2.2 Model Selection and Evaluation

Matos (2023) utilized a database built from the CSP 2 database, which contains information on 368 global dam failures since 1915. However, due to incomplete data, the final analysis included 66 dams. Matos' methodology employed various combinations of variables as input to train predictive models using the K Nearest Neighbors (KNN) algorithm in Python. The models were evaluated using the accuracy metric, with the most accurate model (excluding the volume variable and using 3 neighbors) achieving a 71% accuracy rate.

The final step involved evaluating the effectiveness of implemented risk controls for non-failure TSFs. This analysis assessed how well the controls mitigate identified risks and contribute to the overall safety and resilience of the facilities. The likelihood and potential consequences of identified risks were assessed based on TSF type. This evaluation aimed to inform the definition and implementation of risk controls specific to credible failure modes for TSFs, ultimately enhancing safety measures and mitigating potential risks.

3 RESULTS AND DISCUSSION

3.1 Dam failure database

Analysis of the dam failure database demonstrated its representativeness and identified potential correlations for predicting structural behavior related to failure modes. Notably, 21% of dam failures attributed to seismic liquefaction occurred in regions with very high seismic risk, while 18% were located in temperate climates.

The analysis of construction methods revealed a significant association between upstream construction and specific failure modes. Upstream construction methods were associated with 21% of static liquefaction failures, 19% of seismic liquefaction failures, and 12% of overtopping failures.

Regarding dam material, 15% of failures due to seismic liquefaction involved specific materials. Height and volume did not exhibit a significant influence on failure modes within the analyzed dataset. Figure 1 visually represents the relationships between seismic risk, construction method, climate influence, and TSF type.

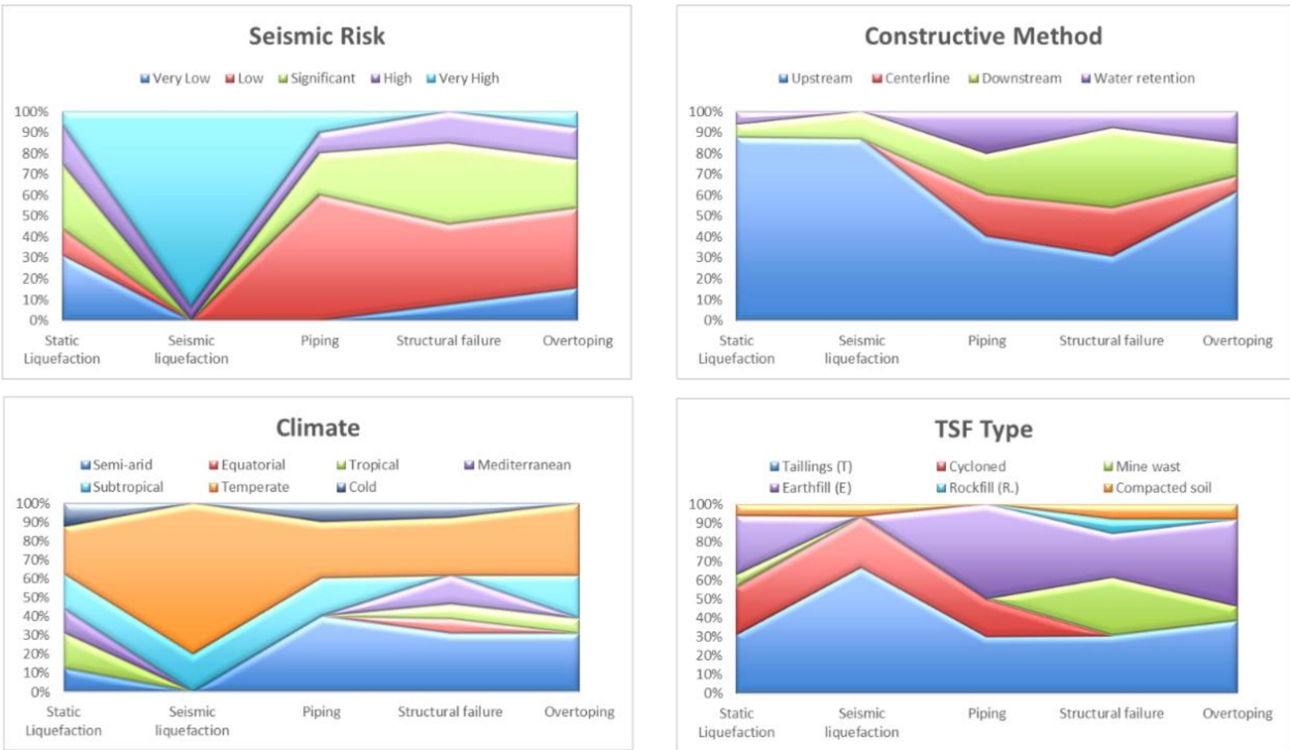

Figure 1. Graphic analysis for key features of TSF on dam failure database.

3.2 Database of TSFs analyzed

Table 1 presents the key characteristics of TSFs alongside the identified credible failure modes. These failure modes were derived from statistical analyses of historical data using the Matos (2023) methodology for predicting credible failure modes.

The findings indicate that "Structural failure" is the most prevalent credible failure mode, highlighting its importance for further investigation and the development of appropriate risk controls. It is important to acknowledge that data quality significantly impacts the results. This emphasizes the need for improved data collection practices for TSFs to ensure more representative outcomes in future studies.

Table 1. TSFs Dataset and Credible Failure Modes Based on Statistical Analyses of Historical Data (Matos, 2023).

TSF	Constructive method	TSF Type	Vol. Mm³	Height m	Climate	Hazard Seismic	Ore Type	Credible failure mode
1	Downstream	Compacted soil	13	85	Tropical	Very Low	Nb	Structural failure
2	Downstream	Compacted soil	34	90	Tropical	Very Low	Nb	Structural failure
3	Downstream	Compacted soil	36	89	Tropical	Very Low	Nb	Structural failure
4	Upstream	Tailings	129	165	Tropical	Low	Fe	Structural failure
5	Upstream	Tailings	10	55	Tropical	Low	Fe	Structural failure
6	Dry Stack	Talings; Waste	4.4	80	Tropical	Low	Fe	Piping
7	In Pit	In Pit	2.9	30	Tropical	Low	Fe	-
8	Upstream	Tailings	59	70	Semi-arid	High	Cu	Structural failure
9	Upstream	Tailings	1	37	Semi-arid	High	Cu	Structural failure
10	Upstream	Tailings	23	98	Tropical	Very Low	Fe	Structural failure
11	Downstream	Compacted soil	11	39	Tropical	Very Low	Fe	Piping
12	Upstream	Compacted soil	9	77	Tropical	Very Low	Fe	Structural failure
13	Upstream	Compacted soil	19	35	Tropical	Very Low	Fe	Piping
14	Upstream	Compacted soil	31	51	Tropical	Very Low	Fe	Structural failure

TSF	Constructive method	TSF Type	Vol. Mm³	Height m	Climate	Hazard Seismic	Ore Type	Credible failure mode
15	Upstream	Rock	2	61	Tropical	Very Low	Fe	Structural failure
16	Upstream	Tailings	6	85	Tropical	Very Low	Fe	Structural failure
17	Upstream	Compacted soil	503	45	Tropical	Very Low	Fe	Structural failure
18	Upstream	Compacted soil	209	68	Tropical	Very Low	Fe	Structural failure
19	Downstream	Compacted soil	141	34	Tropical	Very Low	Cu	Piping
20	Upstream	Tailings	37	86	Tropical	Very Low	Fe	Structural failure
21	Upstream	Tailings	23	98	Tropical	Very Low	Fe	Structural failure
22	In Pit	In Pit	0,3	11	Tropical	Very Low	Cu	-
23	Downstream	Compacted soil	0,5	25	Tropical	Very Low	Cu	Piping
24	Center line	Tailings	2	21	Tropical	Very Low	Zn; Pb	Structural failure
25	Downstream	Tailings	15	44	Tropical	Very Low	Zn; Pb	Structural failure
26	Downstream	Tailings	3	33	Tropical	Very Low	Zn; Cu; Pb	Structural failure
27	Center line	Tailings	4	132	Desert	High	Zn; Cu; Pb	Liquefaction Seismic
28	Center line	Tailings	3	35	Semi-arid	High	Zn; Cu; Pb	Structural failure
29	Dry Stack	Tailings	7	15	Tropical	High	Zn; Pb	Structural failure
30	Upstream	Tailings	26	30	Tropical	Low	Coal	Slope Instability

4 CONCLUSIONS

This study analyzed a dam failure database and identified promising results for predicting tailings storage facility (TSF) behavior related to failure modes. The analysis suggests a strong correlation between several factors and specific failure types. The significant insights are:

- **Seismic Risk and Climate:** Seismic liquefaction failures were most prevalent (21%) in very high seismic risk zones, with 18% occurring in temperate climates. This suggests a link between geographical conditions and liquefaction risk.
- **Construction Method:** Upstream construction methods were significantly associated with specific failures: 21% of static liquefaction, 19% of seismic liquefaction, and 12% of overtopping failures. This highlights the importance of considering construction methods when assessing TSF vulnerability.
- **Dam Material:** While not as prominent as other factors, dam material played a role in 15% of seismic liquefaction failures, indicating a potential material-specific risk.
- **Height and Volume:** These factors did not show a significant influence on failure modes within the analyzed dataset.
- **Predominant Failure Mode:** "Structural failure" emerged as the most common credible failure mode based on the analysis of TSF characteristics (Table 1). This finding emphasizes the need for further investigation and development of robust risk controls to address structural vulnerabilities.

The study acknowledges the importance of high-quality data for obtaining representative results. Improvements in TSF data collection practices are crucial to ensure more reliable predictions and risk assessments in future studies.

This analysis provides valuable insights for TSF management. By understanding the relationships between various factors and failure modes, engineers and risk management professionals can prioritize actions and resources to enhance TSF safety and minimize the risk of catastrophic failures.

ACKNOWLEDGMENT

We would like to thank National Council for Scientific and Technological Development (CNPq), Coordination of Superior Level Staff Improvement (CAPES) and Minas Gerais State Foundation for Research Support (FAPEMIG - Grant APQ501-21) to support this research.

REFERÊNCIAS BIBLIOGRÁFICAS

CSP 2 -Tailings Dam Failures 1915–2016 (2024). TSF Failures from 1915 : CSP2 (Accessed 16 March 2024).

GTR (2020) *Global Industry on Tailings Management (GISTM)*. Global Tailings Review org. 5th de August 2022.

Huang, J., You, J-X., Liu, H-C., Song, M-S. (2020). *Failure mode and effect analysis improvement: A systematic literature review and future research agenda.* Reliability Engineering & System Safety .Volume 199, July 2020, 106885

ICMM (2021a) *Tailings Management. Good practice guide.* Global Industry Standard on Tailings Management.

ICOLD (2017) *Internal erosion of existing dams, Levees and Dikes, and their foundations.* Committee on Dam Safety. International Commission on Large Dams (ICOLD). Final Draft December 2019.

ICOLD (2019) Incident database Bulletin 99 update. Statistical analysis of dam failures. Committee on Dam Safety. International Commission on Large Dams (ICOLD). Final Draft December 2019.

Machado, N. c. (2017). Retroanálise da Propagação Decorrente da Ruptura da Barragem do Fundão com Diferentes Modelos Numéricos e Hipóteses de Simulação (Dissertação de Mestrado). Apresentada ao curso de Engenharia civil, Universidade Federal de Minas Gerais, Belo Horizonte, out, 159 f.

MATOS, J. M. (2023) Modo de Falha crível em *Barragens de Rejeito de mineração: Uma análise das variáveis condicionantes e proposição de um modelo preditor*. TCC - Final Course Work. Federal University of Ouro Preto. Brazil.

Robertson, P. K., Fear, C. E. (1997) *Liquefaction of sands and its evaluation.* Earthquake Geotechnical Engineering, Ishihara (ed.) Balkema, Rotterdam, ISBN 905410578X. University of Alberta, Edmonton, Alb., Canada

Silva, M. F. da. (2020). Análise espacial dos impactos socioambientais provocados pelo rompimento de duas barragens de rejeitos de mineração: Fundão, na cidade de Mariana e Córrego do Feijão, no município de Brumadinho (Minas Gerais – Brasil). Territorium, 28(I), 67–92. https://doi.org/10.14195/1647-7723_28-1_5

Silva, R.R.P and Meguet, E. (2021). Estudo de Ruptura hipotética de uma pilha compartilhada de estéril e rejeito - Estudo de Caso. XXIV Simpósio Brasileiro de Recursos Hídricos (ISSN 2318-0358).

WISE (2024) *Chronology of Major Tailings Dam Failures*. Uranium Project. https://www.wise-uranium.org/mdaf.html (Accessed 16 March 2024).