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Tailings dam decommissioning projects in Brazil: challenges, remote technologies and lessons learned

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Abstract

Recent tailings dam failures in Brazil have driven regulatory reform and accelerated mandatory decommissioning of upstream-raised and facilities of uncertain construction method. Under the National Mining Agency (ANM) framework, strict access limits that constrain conventional investigations, monitoring and construction are imposed on high-risk (Level 3) dams. Consequently, projects increasingly deploy remote and unmanned technologies – robotic cone penetration testing with pore pressure measurement (CPTu) rigs for in situ characterisation, unmanned vehicles for earthworks and lift line spider systems for controlled personnel access, supported by real-time instrumentation to track geotechnical behaviour during closure. This paper summarises Brazilian experience with 3 decommissioning strategies: full tailings removal, partial removal and downstream buttress construction, selected according to geometry, emergency level, access and environmental constraints. Preventing liquefaction during earthworks emerged as a primary challenge; vibration surveillance systems were implemented to monitor equipment-induced ground motions, define trigger action response plan (TARP) thresholds and inform operational controls. The study distils practical lessons and outlines transferable approaches to improve safety and efficiency in tailings dam decommissioning internationally.

Keywords: *tailings, TSF decommissioning, remote investigation technologies*

1 Introduction

1.1 Background on mining in Brazil

Mining is a cornerstone of Brazil's economy and one of its most globally competitive sectors. The country ranks among the world's largest producers of iron ore, bauxite, gold and copper, with extraction and processing concentrated in major mineral provinces such as the Quadrilátero Ferrífero in Minas Gerais and the Carajás Province in Pará. According to the IBRAM (Brazilian Mining Institute) Sector Mineral 2025 report, the mining sector generated approximately USD60 billion in 2025 and supported around 230,000 direct jobs, underscoring its central role in national economic development (IBRAM 2025).

The scale of Brazil's mineral production is directly reflected in the magnitude of its tailings generation. National mining activities produce in the order of 200–250 million tonnes of tailings per year, driven by intensive comminution and wet concentration processes that have historically relied on conventional wet tailings storage facilities (TSFs) for containment. A significant proportion of these facilities, particularly in iron ore operations, consist of fine-grained, contractive tailings deposited under saturated conditions, often within upstream-raised structures. These characteristics increase susceptibility to static liquefaction under undrained loading conditions and represent a critical challenge for both dam safety and closure design. The magnitude of these tailings volumes, combined with the progressive urban expansion around many TSFs,

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particularly in densely populated regions such as Minas Gerais, significantly elevates geotechnical and regulatory exposure. This expansion increases the potential consequences of any structural instability. This combination of high production, large tailings inventories and encroaching urban development makes Brazil especially vulnerable to tailings-related risks and provides essential context for the critical events discussed in the following section.

1.2 Overview of tailings dam failures

Recent catastrophic failures in Brazil – notably the Fundão/Mariana (2015) and Córrego do Feijão/Brumadinho (2019) events, exposed systemic weaknesses in tailings governance and triggered a major regulatory and industry response. These disasters caused large loss of life, long-lasting environmental damage (river contamination, ecosystem loss; Carmo et al. 2017) and severe socio-economic impacts for affected communities and companies; they also prompted a reappraisal of how legacy and active tailings facilities are investigated, monitored and closed. As a result, Brazilian regulation now requires stricter classification, continuous monitoring and, for many legacy upstream-raised or facilities where there is uncertainty regarding the construction method, mandatory decommissioning or remediation. This shift has fundamentally repositioned decommissioning from a long-term closure objective to an urgent risk reduction measure for high-consequence structures.

1.3 Changes in Brazilian regulations

Following the Mariana (2015) and Brumadinho (2019) disasters, Brazil undertook a comprehensive overhaul of its tailings governance framework. As of 2024, the National Mining Agency (ANM – Agência Nacional de Mineração) has implemented a series of updated laws, resolutions and technical norms aimed at strengthening dam safety, improving transparency and ensuring more rigorous oversight of tailings facilities. These instruments collectively redefine the expectations for design, monitoring, emergency preparedness and decommissioning, aligning national practice with international standards such as the *Global Industry Standard on Tailings Management* (GISTM). Table 1 summarises the principal regulations currently governing tailings management in Brazil.

Table 1 Norms related to tailings management in Brazil

Norm	Key points
Law No. 14.066 /2020 (Federal Law on Dam Safety) (Federative Republic of Brazil 2020)	• Establishes stricter safety requirements for all dams in Brazil, including mining tailings dams. • Mandates emergency action plans (PAE) for all high-risk dams. • Requires independent safety audits for critical structures. • Increases penalties for non-compliance.
ANM Resolution No. 95/2022 (New Tailings Dam Safety Regulation) (ANM 2022a)	• Replaces previous resolutions (e.g. DNPM 70.389/2017) and aligns with the *Global Industry Standard on Tailings Management* (GISTM). • Ban on upstream dam construction. • Mandatory decommissioning plans for inactive dams. • Periodic safety reviews (every 3 years for high-risk dams). • Real-time monitoring for critical structures.

Norm	Key points
ANM Normative Instruction No. 79/2022 (Technical Requirements for Tailings Dams) (ANM 2022b)	• Defines geotechnical, structural and operational standards for TSFs. • Requires completion of a failure mode and effects analysis (FMEA). • Stricter criteria for dam stability assessments. • Obligatory public disclosure of safety reports.
ANM Resolution No. 13/2021 (Emergency Protocols & Early Warning Systems) (ANM 2021a)	• Mandates 24/7 monitoring systems for high-risk dams. • Requires community alert systems in downstream areas.
ANM Resolution No. 91/2021 (Financial Guarantees for Dam Decommissioning) (ANM 2021b)	• Ensures mining companies set aside funds for dam closure and post-closure maintenance.

These regulatory changes have significantly altered engineering practice in Brazil, particularly through the prohibition of upstream dam construction and the mandatory decommissioning of legacy structures – requirements that exceed those in many other jurisdictions. In practice, this has accelerated closure timelines and driven the adoption of advanced monitoring systems and innovative construction methods under high-risk conditions.

1.4 Importance of decommissioning tailings dams

Decommissioning tailings dams is a key component of responsible mine closure, directly reducing risks associated with legacy structures and improving long-term environmental and community safety. It helps prevent failures, supports ecosystem restoration through tailings removal or stabilisation, land regrading and re-vegetation, and contributes to long-term stability. The verification of performance through monitoring helps confirm the reliability of the decommissioning approach and provides early warning if conditions deteriorate, while also supporting regulatory compliance under increasingly stringent national requirements.

From an engineering perspective, decommissioning follows a risk-reduction hierarchy of full removal where feasible and structural stabilisation when removal is impractical. This approach aligns with the GISTM, which requires closed facilities to remain ‘stable in perpetuity’. Meeting this expectation demands robust geotechnical design and reliable monitoring systems to verify the design intent.

In Brazil, these technical requirements intersect with social licence expectations, particularly in regions where communities live near TSFs. Transparent communication, visible risk reduction actions and demonstrable improvements in safety performance are now essential to rebuilding public trust. These factors, combined with the scale of legacy upstream dams and regulatory urgency, have made decommissioning a central challenge for the mining industry and a key driver for innovation in geotechnical engineering and construction practices. Together, these factors explain why decommissioning, already a well-established priority in many mining jurisdictions, has become a renewed national focus and a central element of modern tailings governance in Brazil.

2 Brazilian regulation and risk classification

2.1 Classification of dams according to risk levels

Brazilian tailings dam regulation establishes a structured risk classification system that determines the level of monitoring, operational restrictions and intervention measures required for each facility. This framework – reinforced by Law No. 14.066 /2020 and detailed in ANM Resolution No. 95/2022 – evaluates dams based on their structural integrity, potential environmental and social consequences and proximity to downstream communities. The classification supports consistent decision-making and ensures that resources are directed to the structures presenting the greatest risk. Beyond regulatory categorisation, this classification directly influences engineering design criteria, investigation strategies, monitoring requirements and the selection of decommissioning methodologies.

There are 3 regulatory risk levels.

2.1.1 Level 1 (low risk)

These are facilities with no significant structural anomalies and limited potential for environmental or social impact. These dams require routine inspections and compliance with standard operational and monitoring procedures.

2.1.2 Level 2 (medium risk)

These are dams presenting moderate structural concerns or located in areas where failure could cause notable environmental or operational impacts. These structures require more frequent inspections, detailed stability assessments and enhanced monitoring, as required under ANM Normative Instruction No. 79/2022.

2.1.3 Level 3 (high risk)

These are facilities with severe structural deficiencies or located in areas where failure could result in catastrophic environmental and human consequences. Access to these dams is heavily restricted and the dams must be equipped with continuous monitoring systems and emergency alert mechanisms, in accordance with ANM Resolution No. 13/2021. High-risk dams are also prioritised for mandatory decommissioning or stabilisation, as established in ANM Resolution No. 95/2022.

In practice, Level 3 classification imposes significant constraints on engineering activities, often limiting direct personnel access and requiring the adoption of remote or unmanned technologies for site investigation, monitoring and construction. These conditions substantially influence execution strategies and risk management approaches during decommissioning. This classification system plays a central role in Brazil's post-Brumadinho regulatory landscape, enabling authorities and operators to prioritise safety actions, allocate resources efficiently and implement risk reduction measures consistent with national legislation and international standards such as the GISTM. As a result, the classification system functions not only as a regulatory framework but also as a key driver of engineering decisions in tailings dam decommissioning projects in Brazil.

2.2 Impact of being in a determined emergency level

In addition to risk classification, emergency levels define the immediacy of response and impose progressively stricter operational constraints, particularly for dams under conditions of potential or ongoing instability. Risk classification reflects the inherent characteristics and potential consequences of a dam, whereas emergency level indicates its current condition and the urgency of required actions. Higher emergency levels trigger progressively stricter requirements for monitoring, access control and risk reduction actions, ensuring that facilities presenting elevated risk receive immediate and proportionate intervention.

Recent dam safety audits conducted for the Public Ministry of Minas Gerais, as documented by Ritchie and Baumgardner (2023), show that dams assigned to elevated emergency levels require enhanced geotechnical characterisation, continuous monitoring and strengthened emergency preparedness to manage credible failure modes during closure. Their case studies reinforce that emergency level designation is not only a regulatory status but a direct indicator of the operational controls and risk mitigation measures needed throughout decommissioning.

2.2.1 Emergency preparedness

Dams classified at the highest emergency levels must implement comprehensive emergency action plans, including community evacuation routes, communication protocols and real-time monitoring systems, as mandated by Law 14.066/2020 and ANM Resolution 13/2021. These plans ensure rapid response capability in the event of structural instability.

2.2.2 Access restrictions

High-risk facilities (Level 3) are subject to strict access limitations to protect workers and prevent unauthorised entry. In some cases, operators must rely on lift-line systems to conduct inspections and maintenance safely – an approach increasingly adopted in Brazil due to the restricted access conditions imposed by ANM Resolution 95/2022. For site investigation and construction, remote-controlled equipment and unmanned vehicles are used to operate with restricted access.

2.2.3 Monitoring and surveillance

Continuous monitoring is mandatory for dams in elevated emergency levels. This includes the installation of real-time geotechnical instrumentation, automated data transmission and frequent stability assessments, consistent with the technical requirements of ANM Normative Instruction No. 79/2022. These systems are essential for detecting early signs of deformation, pore pressure rise, or other precursors to failure. Such systems are critical to support real-time decision-making during earthworks, particularly in materials susceptible to liquefaction and under conditions of restricted access.

2.2.4 Decommissioning requirements

Dams classified as high risk are prioritised for mandatory decommissioning or stabilisation, as required by ANM Resolution 95/2022. This may involve tailings removal, downstream buttressing, or other engineered interventions designed to eliminate or substantially reduce failure potential.

Overall, the emergency level framework not only ensures appropriate regulatory oversight but also imposes significant constraints on engineering execution, particularly by limiting access, increasing monitoring requirements and accelerating the implementation of risk reduction measures. These conditions have been a primary driver for the adoption of remote technologies in Brazilian tailings dam decommissioning projects.

3 Methods of tailings dam decommissioning: approaches and considerations

Tailings dam decommissioning is a critical phase of mine closure and long-term risk reduction for existing facilities. Selecting an appropriate decommissioning method requires careful evaluation of dam geometry, geotechnical conditions, regulatory obligations, environmental constraints and project economics. The following subsections present the principal decommissioning approaches used in Brazil, along with key considerations such as licensing requirements, borrow material availability and site-specific operational constraints according to Vizcarra (2023).

3.1 Overview of decommissioning methods

Figure 1 illustrates the 3 principal decommissioning strategies commonly applied in Brazil – full removal, partial removal, and downstream buttress construction – each selected based on site-specific geotechnical, operational and regulatory constraints. The following subsections summarise the characteristics, advantages and limitations of each method.

3.1.1 Full removal

Full removal involves complete dismantling of the dam structure, with tailings relocated to a more stable facility or reprocessed; this strategy is typically used for high-risk dams where partial removal or buttressing is unfeasible. However, this method faces challenges including high costs, logistical complexity and potential secondary environmental impacts during material relocation.

3.1.2 *Partial removal*

Partial removal involves selectively extracting tailings from unstable dam sections (especially the crest) and relocating the tailings to a licensed facility, while constructing a stabilising toe embankment and reinforcing the remaining structure. This method is used when full removal is cost-prohibitive but risk reduction is still achievable, provided the toe area is accessible and unobstructed and when approved relocation sites and material sources are available nearby.

3.1.3 *Buttress construction (reinforcement of existing structure)*

Buttress construction reinforces existing dam structures by building a supporting downstream embankment, typically employed when dams have structural weaknesses without imminent failure risks or when complete removal is impractical due to large material volumes. However, this method faces challenges, including the need for additional borrow materials and potential requirements for ongoing maintenance.

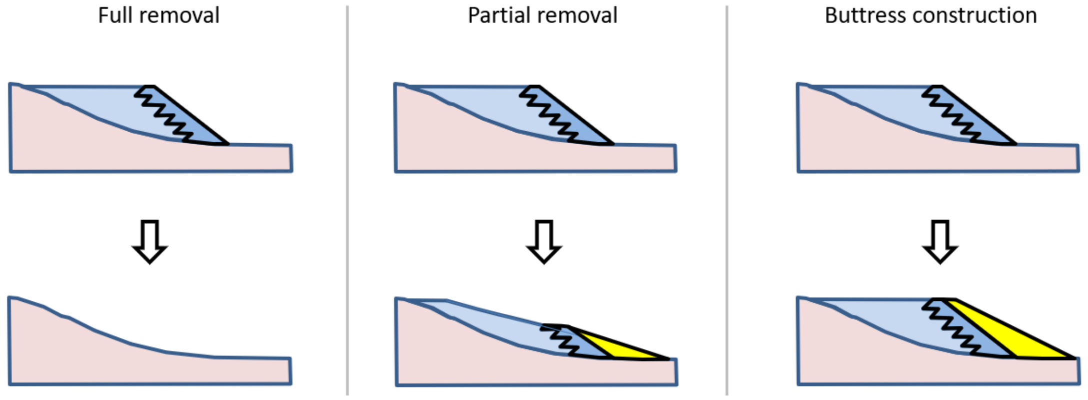

Figure 1 Decommissioning methods

3.2 Criteria for selecting a decommissioning method

The selection of an appropriate decommissioning strategy depends on a combination of regulatory, technical, logistical and economic factors. These criteria guide engineers in determining whether full removal, partial removal, or buttress construction is the most viable and defensible option for a given site. Table 2 summarises the principal considerations that influence method selection.

Table 2 Criteria for selecting the decommissioning method

Norm	Key points
Licensing	• Is there sufficient area at the dam toe to construct a buttress or perform partial removal? • Can the removed material be disposed of in another facility or reprocessed?
Cost	• Is this option economically feasible compared to alternatives?
Complexity	• Are the necessary equipment and construction techniques available to ensure successful implementation of this method?
Interferences	• Are there any obstructions (e.g. rivers, railways, powerlines) that cannot be relocated and might hinder buttress construction or partial removal?
Borrow material availability	• Is there sufficient suitable material available that meets project specifications for embankment construction? • Is this material source located near the site and economically viable to use?

Selecting the right decommissioning method for tailings dams involves balancing technical, environmental, regulatory and economic factors. While full removal offers the highest level of risk reduction, alternatives like buttressing or in situ closure may be more practical in certain scenarios. Proper planning, stakeholder engagement and compliance with licensed area requirements are essential for successful decommissioning.

4 Challenges in project development

The decommissioning of tailings dams presents several technical and logistical challenges that must be carefully addressed during project planning and execution. These are outlined in below.

4.1 Review of existing data and limitations

- Incomplete or outdated records: historical dam designs, construction methods and stability assessments may be missing, inconsistent, or based on obsolete standards.
- Data reliability: legacy data (e.g. geotechnical reports, hydrological studies) may lack sufficient detail for modern risk modelling.
- Regulatory changes: older dams may not comply with current safety and environmental regulations, requiring additional studies.

4.2 Ground investigation difficulties

Drilling constraints:

- Fluid restrictions: in unstable or saturated tailings, fluid-free drilling (required to avoid liquefaction risks) significantly complicates sample collection.
- Access limitations: steep slopes or soft tailings surfaces often impede rig mobilisation and positioning.

Remote testing challenges:

- CPTu (cone penetration testing with pore pressure measurement): high-risk dams frequently impose access restrictions for human operators, necessitating the use of unmanned/robotic CPTu equipment for safe data collection.

4.3 Geotechnical monitoring challenges

4.3.1 Instrument readings

- High-risk dams impose access restrictions for personnel conducting geotechnical instrument readings. To address this challenge, solutions such as helicopter transport with personnel secured by attached lifelines have been implemented.
- A singular alternative is the lift line spider system, illustrated in Figure 2, which consists of a suspended lift line anchored to 4 towers positioned in safe zones (Andrade et al. 2022). Personnel are secured to the line and can traverse the dam crest or downstream face while remaining continuously supported, enabling controlled access for instrument readings and allowing immediate evacuation to a safe zone in the event of an emergency. Although effective for restricted access conditions, these methods were evaluated for their inherent risks and financial implications. Their use is therefore justified only under circumstances.

4.3.2 Trigger monitoring

Vehicle traffic can induce local liquefaction in saturated, loose tailings, potentially triggering progressive liquefaction events that may lead to facility failure. Resent research also shows that machinery-induced vibrations can act as cyclic loading on contractive tailings, depending on amplitude, frequency content and the natural frequency of the tailings (Tan & Ghahreman-Nejad 2024).

To mitigate vibration-related risks during decommissioning:

- A vibration monitoring system is installed to track vibrations from earthworks equipment.
- The system provides alerts when vibration levels approach TARP thresholds.
- Field calibration is conducted through excavation trials to establish vibration and pore pressure response baselines.

These hurdles underscore the need for tailored solutions in tailings dam decommissioning, particularly in complex environments like Brazil.

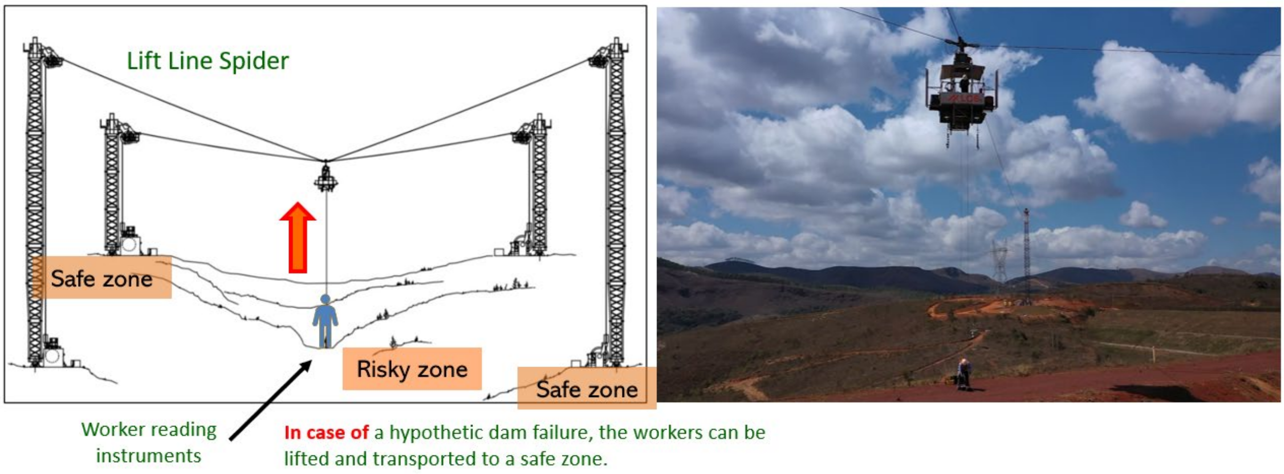

Figure 2 Lift line spider system

5 Engineering project considerations

Engineering design and execution in tailings dam decommissioning are strongly influenced by site-specific constraints that affect constructability, safety and overall project feasibility, particularly in high-risk facilities.

5.1 Importance of licensed areas

Regulatory compliance necessitates approved areas for borrow material extraction (clay, rock or engineered fill), temporary tailings stockpiling and final disposal/reprocessing, yet challenges persist, including limited nearby licensed sites, protracted permitting delays and potential requirements for additional environmental impact assessments.

These constraints directly influence the feasibility of decommissioning alternatives, particularly those requiring significant material movement such as buttress construction or partial removal. Delays in licensing may also impact project schedules and limit flexibility in construction sequencing.

5.2 Operational constraints: managing infrastructure and natural barriers in TSF decommissioning

Mine components and natural geography near TSFs – such as active operations, open pits, rivers, lakes, pipelines and powerlines – often obstruct decommissioning work, requiring solutions like phased closures or infrastructure relocation to mitigate conflicts. These constraints highlight the importance of planning for closure from the outset of operations, as early integration of decommissioning requirements can significantly reduce access limitations and avoid costly retrofits. For many existing TSFs, however, closure was not considered during initial design, making conflict mitigation strategies essential.

5.3 Resource challenges: addressing shortages of geotechnical experts and specialised equipment

The industry continues to face significant shortages of qualified geotechnical tailings engineers, a challenge intensified by rising global standards and the increasing complexity of decommissioning projects. Small, Bjelkevik and Witte (2024) highlight a widening talent gap driven by a lack of skilled tailings-focused specialists, impending retirements among senior practitioners who hold most of the sector's deep technical expertise and limited formal training pathways at undergraduate and masters levels. This shortage is particularly acute in Brazil, where recent regulatory changes require mining operators to decommission upstream tailings dams within legally mandated deadlines, sharply increasing demand for experienced geotechnical and tailings professionals. To mitigate these pressures, operators have begun supporting university programs and graduate pathways in partnership with local institutions, helping expand academic exposure to tailings engineering and strengthen the pipeline of future specialists. These combined efforts reinforce the need for broader education, structured mentoring and professional development programs to build sustainable technical capacity.

In parallel with personnel shortages, operators face limited access to specialised investigation equipment such as cone penetrometer test (CPT) rigs and drilling systems that meet the strict safety condition requirements of the mining industry. These stringent verification checks make equipment mobilisation difficult, as many drilling contractors do not maintain machinery in a condition fit for on-site deployment. Competition from active mining operations, combined with the limited number of compliant units available, further restricts access, creating scheduling bottlenecks and slowing progress on decommissioning programs. To mitigate these constraints, operators increasingly rely on partnerships with site investigation companies and laboratory service providers, enabling early resource commitment, coordinated planning and progressive strengthening of regional service provider capability.

5.4 Trafficability solutions

Trafficability solutions for tailings dam decommissioning require specialised ground improvement techniques to stabilise weak, saturated surfaces, including the construction of temporary haul roads using engineered fill materials to create safe working platforms. Amphibious vehicles prove indispensable in these operations, enabling equipment mobility across ultra-soft deposits that would immobilise conventional machinery, while rigorous stability controls mitigate liquefaction risks near ponded areas or in vulnerable tailings deposits during critical decommissioning activities (Figure 3).

Figure 3 (a) Amphibious excavator; (b) Saturated tailings

5.5 Remote technology advancements in dam decommissioning

The adoption of remote-controlled and unmanned equipment has transformed the safety and efficiency of tailings dam decommissioning, particularly in Brazil where Level 3 emergency classifications impose strict access restrictions. Remote CPT rigs with real-time data transmission enable subsurface characterisation without exposing personnel to unstable zones, while robotic dozers and GPS-guided machinery allow precise embankment construction in marginally stable areas and under adverse weather conditions. As illustrated in Figure 4 (unmanned vehicles), these platforms provide safe, reliable operation in areas where conventional equipment cannot be deployed, significantly reducing worker exposure and enabling continuous progress across challenging foundation soils.

The accelerated use of unmanned systems is exemplified by a large-scale decommissioning project, where remote-controlled excavators, dozers and articulated trucks enabled large-scale tailings removal under emergency-level constraints. As documented by Araujo et al. (2024), productivity increased from approximately 50 m³/h at project initiation to more than 100 m³/h as remote operation shelters, redundant fibre-optic networks and semi-autonomous control kits were deployed and optimised. This case demonstrates how remote-controlled earthmoving technologies – such as those shown in Figure 3 – not only mitigate geotechnical and safety risks but also enhance operational performance, establishing a new benchmark for dam closure in high-risk settings.

Figure 4 Unmanned vehicles used in tailings dam decommissioning

Overall, these engineering considerations demonstrate that decommissioning projects are not only governed by design criteria but also by execution constraints, which are particularly severe in high-risk facilities. These conditions frequently necessitate adaptive methodologies, phased construction approaches and the adoption of remote technologies to safely perform works in areas with limited access, low trafficability and elevated geotechnical risk.

6 Case study: decharacterisation of tailings dyke in the Iron Quadrangle, Minas Gerais, Brazil

A case study from Minas Gerais' Iron Quadrangle (Gonçalves et al, 2023) demonstrates a successful example in tailings dam decommissioning. In this project an 8.8 million m³ upstream dyke was successfully transformed through partial removal and downstream embankment construction (3.5% slope) (Figure 5). The project employed comprehensive geotechnical investigations (including CPTu and triaxial tests) and real-time monitoring with 68 piezometers and geophones to verify pore pressure behaviour and vibrational response during construction. Updated analyses using these data confirmed that the reshaped landform reached a Factor of Safety of 1.6, exceeding the 1.5 regulatory requirement. The 8-stage phased approach addressed critical challenges like saturated tailings excavation through dry-excavation protocols and load corridors, while innovative drainage solutions used existing ponds for sediment capture.

The project's achievements show effective strategies for complex decommissioning scenarios. The measures highlighted in this section focus specifically on stability and liquefaction-related controls, which formed the critical risk drivers for this case study. Other closure criteria, such as environmental performance, contamination management, erosion control and long-term landform stability, were addressed in the broader decharacterisation program but are not the emphasis of this article.

Rigorous independent design reviews and adaptive measures, such as vibration-triggered work suspensions, enhanced operational safety for on-site personnel during earthworks. These methods, developed in response to Brazil's stringent regulations, offer valuable insights for global tailings management, particularly in addressing liquefaction risks and optimising material re-use in dam decharacterisation projects.

Figure 5 Orthophotos; (a) Before decommissioning works; (b) After decommissioning

7 Vibration risk management in tailings dam decommissioning

To analyse triggering mechanisms for assessment of liquefaction risk and to support equipment selection during decommissioning works, a study on vibration dynamics during tailings dam decommissioning, documented by Ramos et al. (2023), was undertaken in a Brazilian TSF decommissioning project involving iron ore tailings. The study evaluated equipment-specific vibration behaviour using advanced seismograph monitoring at the surface and at 8 m depth. The monitoring campaign quantified how vibrations generated during earthworks attenuate with depth, showing substantial reductions during excavation and embankment construction activities. Hydraulic excavators produced the highest peak vibrations, reaching 143 mm/s during bucket strikes, whereas dump trucks generated minimal impacts below 1.5 mm/s.

While the results provide valuable quantitative insight for operational planning, the authors emphasise that vibration propagation and liquefaction susceptibility are heavily dependent on tailings type, density, saturation and stratigraphy. Therefore, these findings, although derived from iron ore tailings, should be applied with site-specific evaluation rather than assumed universal across all tailings deposits. Overall, the study contributes to developing safer operational protocols in unstable tailings environments and informs equipment selection for decommissioning projects.

7.1 Precision monitoring and safety thresholds

The study established precise vibration profiles for each equipment type, with excavator bucket strikes creating vibrations that are 3–6 times greater than bulldozer operations. Depth monitoring confirmed consistent vibration attenuation without amplification, enabling the development of predictive decay models. These technical insights directly informed TARPs, defining conservative vibration thresholds for systematic work suspension. The research further validated that dump truck operations remained safely below this threshold, even in high-risk zones (Figure 6).

Figure 6 Damping tests of dump truck operations to characterise vibration decay in tailings (Ramos et al, 2023)

7.2 Regulatory applications and global best practices

This work provides essential technical support on vibration control during dam decommissioning. The methodology – combining real-time monitoring with predictive modelling – sets a new standard for risk management in liquefaction-prone TSFs. The findings specifically recommend preferential use of dump trucks in sensitive zones, restricted excavator operations with continuous monitoring, and depth-adjusted vibration thresholds. These protocols offer a transferable framework for tailings management worldwide, particularly for upstream dam remediation projects where vibration-induced liquefaction remains a primary failure risk. Future applications could integrate these models with automated monitoring systems for enhanced safety during critical decommissioning phases.

8 Final considerations

The future of tailings dam decommissioning will be driven by rapid technological evolution, stricter alignment with the GISTM and an increasingly integrated approach that balances engineering innovation, regulatory compliance and long-term sustainability. This paper focuses specifically on liquefaction-related stability controls, as liquefaction represented the dominant risk driver for the case study. Other rehabilitation criteria, such as environmental performance, contamination management, erosion control and long-term landform stability, were addressed within the broader decharacterisation program but fall outside the scope of this technical discussion.

Advanced remote and robotic equipment will continue to enhance operational safety for on-site personnel in high-risk operational environments, enabling work in areas where human access is restricted due to unstable tailings conditions and access limitations defined by Brazilian legislation for high-risk facilities. The decommissioning of legacy dams requires strategies that fully embrace GISTM's expectation that facilities remain stable in perpetuity, addressing persistent challenges such as saturated tailings, limited access and cost constraints. Brazilian case studies, especially those in Minas Gerais where communities are located close to TSFs, demonstrate that successful decommissioning relies on phased execution supported by robust monitoring frameworks, including vibration-control thresholds, standardised risk assessment protocols and transparent community engagement practices.

Use of artificial intelligence disclosure statement

Microsoft Copilot was used during manuscript preparation to enhance language quality and clarity. The authors carefully reviewed and revised all AI-assisted text and accept full responsibility for the accuracy and integrity of the final content.

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