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Risk considerations for Brazilian tailings dam closure

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Abstract

The January 25, 2019 failure of the Corrego de Feijao tailings dam in Brumandinho, Brazil owned by Vale S.A. resulted in 270 lives lost along with significant environmental and cultural heritage impacts. Pursuant to this failure the Public Ministry of the State of Minas Gerais (MPMG) initiated a series of dam safety audits to enhance dam safety oversight and effect change within the Brazilian mining industry, concurrently with the Brazilian National Mining Agency (ANM) issuing legislation in February 2019 requiring the removal or stabilization and decharacterization (deregistration) of all upstream tailings dams.

This paper discusses the dam closure risk considerations and experience on various dam safety audits carried out by SLR Consulting (Canada) on behalf of MPMG. The audits involved dams raised by a variety of methods including the upstream method founded on deposited tailings. In general, the focus of the technical audits included geotechnical characterization of the dam and foundation, dam design and construction stewardship, public and worker safety, and emergency preparedness, from the perspectives of both Brazilian regulations and international tailings and dam safety practice. Case studies are presented within three groupings to highlight various experiences: modifications introduced for works that had been carried out prior to commencing the audits, works designed and executed during the audit oversight, and design and planning considerations for closure works that are in progress for high-risk upstream-raised tailings dams. For all cases, the long-term risks, credible failure modes, and operational controls during construction are discussed.

The Group 1 case studies highlight the importance of a holistic, long-term risk management perspective. The dam discussed was decharacterized as a mining dam prior to commencing the dam safety audits but was deemed susceptible to credible failure modes including slope instability, erosion, and spillway downcutting. In 2022 the Brazilian national mining agency updated the administration of mining dams to include a minimum of two years of monitoring after completion of the closure works. Notwithstanding, Vale is implementing improvements to the dam as part of their evolving dam safety governance practices in response to audit recommendations.

Closure activities for the two dams in Group 2 involved low risk. Closure was planned and successfully completed within the period of the audits. For these dams, design decisions were made after comparing alternative closure scenarios by long-term objectives, constructability, dam safety during construction, and environmental and social considerations. Construction vibration testing was carried out to ensure construction-induced vibrations did not impact adjacent dams.

The Group 3 case studies discuss design and planning decisions related to decharacterization of three upstream-raised tailings dams, two of which are at emergency levels. Prior to commencing construction dam breach inundation studies were carried out, emergency preparedness and response plans updated, and citizens in the potential inundation zone were evacuated and/or back-up or emergency containment dams were built. Construction planning included consideration of remotely-operated construction equipment, dam instrumentation (geophones, seismographs and piezometers) to detect construction-induce vibrations that could trigger tailings liquefaction, water management, and planning of staged excavations.

Keywords: *tailings liquefaction, dam removal, construction-induced vibrations, dam safety governance*

1 Introduction

SLR Consulting (Canada) Ltd. (SLR) is conducting a series of independent technical audits of dam safety for structures owned by Vale S.A. (Vale) in Brazil. The audits are being carried out under covenant between the Public Prosecutor of the State of Minas Gerais (MPMG), Ministry of Labour of the State of Minas Gerais (MPT) and Vale in response to a series of public actions against Vale.

1.1 Audit context

The frequency of audits and level of involvement depend on the rate at which activities are conducted or changes occur. The adequacy of the design is assessed based on its achievement of good engineering practice under both Brazilian Regulations and international standards.

SLR undertook to carry out sufficient review of the investigations, documentation, and analyses in order to develop an independent opinion on both the general principles of design, construction and operation, and on the validity of the key elements of the design analyses, construction control, operational surveillance and monitoring, and safety.

The main audit components are: geotechnical characterization, dam design and construction stewardship, dam safety and public and worker safety. Audit findings are reported through MPMG within the public purview with progress on recommendations tracked through CIGA (Centro Integrado de Gestão Ambiental) a public database for consolidating information and data from the independent technical audits. The CIGA website (https://caoma-mpmg.org) allows stakeholders and the public to access the audit information.

1.2 Dam safety governance and closure

Tailings and sediment control dams pose different risks throughout the life-cycle which is often considered to be perpetuity. During operations the dams are constantly evolving as the storage capacity is filled and expanded to meet needs. There is also a need to continuously manage an operating pond for collection of precipitation runoff and recirculation of mill make-up water, while maintaining live storage for the environmental design flood, and for the management of extreme storms safely (CDA 2019). Operations are dynamic and evolving, but the presence of staff assists with surveillance and risk management. For the active and passive closure phases (CDA, 2014) passive systems are desirable, in line with reduced surveillance and maintenance.

Routine surveillance and dam safety management guidelines, such as CDA (2013), are part of international dam safety management practices that are not necessarily captured in dam legislation and regulatory approvals in all jurisdictions. To enhance uniformity the global tailings standard (PRI et al. 2020) serves to align corporate governance with societal expectations along environmental, social and governance (ESG) principles. Accordingly, Vale has implemented an enhanced tailings and dam management system and a commitment to dam safety stewardship and governance principles.

2 Risk considerations and lessons

Risk considerations for planning closure of tailings and sediment control dams include: the current safety condition; physical, chemical and ecological stability of the closure configuration; and ability to implement the closure activities safely. Current dam safety aspects include the level of understanding of the geotechnical characterization of the dam foundation, deposited tailings or accumulated sediment, adequacy of design and construction stewardship related to the dam itself, and the safety or workers and the public around the dam.

Planning the implementation of closure activities requires an understanding of the methods proposed, type and number of equipment, and climatic and seismic conditions. All the examples cited herein are within the state of Minas Gerais, Brazil, which has a tropical climate and significant seasonal rains totalling between

660 mm and 2200 mm during the wet between about October and March each year. The balance of the year is generally dry. The significant variation in rainfall between wet and dry seasons is illustrated in Table 1.

Table 1 Climatic conditions in Minas Gerais, Brazil

Season	Average Rainfall (mm)	Temperature Range (˚C)
Wet season (October to March)	1445	18 to 28
Dry season (April to September	164	15 to 26

2.1 Closure examples

Participation on the MPMG dam safety audits has afforded SLR the opportunity to observe and influence the planning and implementation of numerous dam stabilization, closure and decharacterization projects with Minas Gerais as an extension of the dam safety audits. Table 2 lists the dams addressed in this paper.

Table 2 Vale dam closure examples

Dam name (Group)	Attributes	Closure method	Risk considerations
Cobras Fazendão Mine (Group 1)	13.5 m high earthfill embankment dam No dam instrumentation	Closed in-place Sediment surface graded and revegetated Passive spillway	Tailings settlement has resulted in ponding Spillway erosion could result in dam failure
Paracatu Fazendão Mine (Group 2)	22 m high earthfill embankment dam	Full removal	Spillway not adequate for design flood
Auxilary Dyke / Dam 5 Águas Claras Mine (Group 2)	79 m high earthfill embankment dam & 8 m high upstream dyke	Removal of Auxiliary Dyke Sloping tailings surface	Tailings deposited above the dam crest Cyclic mobility of upper terrace tailings
Fernandinho Abóboras Mine (Group 3)	19 m high upstream raised tailings embankment	Full embankment removal and tailings removal above the adjacent pit rim	Low phreatic level in tailings (low risk) Haul route is close to Vargem Grande Dam
Vargem Grande Abóboras Mine (Group 3)	Starter dam with three upstream raises 40 m high	Progressive excavation of tailings and raises Starter Dam to remain for sediment control	Dam stability susceptible to tailings liquefaction Public evacuations
B3/B4 Mar Azul Mine (Group 3)	Stage-raised upstream tailings dam 55 m high Poor knowledge of design / construction	Full removal by progressive excavation of tailings and dam	Dam stability Susceptible to tailings liquefaction Back-up safety dam & public evacuations

The Group 1 dam in Table 1 includes a structure that had been decharacterized (closed) prior to the commencement of the audits that were deemed to have remnant credible failure modes. Through the course of the dam safety audits Vale has committed to addressing these failure modes to reduce the residual risk the structures pose.

The second group highlights dams for which Vale carried out an evaluation of alternatives and either changed the closure plan or introduced revisions to manage the risks. The Group 2 dams in Table 1 were followed closely within the period of the dam safety audit program and have been successfully completed.

The final grouping includes dams where closure activities involve significant risk to the dam in question or adjacent structures. These Group 3 dams involved significant closure execution planning to establish critical controls on construction-induced vibration and flood management concerns to mitigate tailings liquefaction and overtopping failure modes during closure construction.

2.2 Long term risk considerations (group 1)

Common international practice guidelines consider that the design life and responsibility for closure of mining facilities is perpetuity. This is not to say that design criteria guidelines based on the hazard potential are not appropriate. Rather, it is meant to suggest that designing for anything other than long-term physical, chemical and ecological stability should consider the on-going surveillance and maintenance costs as part of corporate dam safety governance. Regulatory approvals are the minimum level of effort.

The Cobras Dam closure is a useful example of inherent long-term risks requiring management.

2.2.1 Cobras closure re-evaluation

Fazendão Mine was originally developed by Mineração Serra Geral, a joint venture between Vale and Kawasaki Steel and has been operational since 1985. The Cobras Dam contains sediments from the operational area of the mine and is located on a tributary of Rio do Carmo and has a catchment of 69 ha. The dam is an earthfill embankment with 13.5 m maximum height, 218 m crest length, impoundment volume of 25,000 m^3.

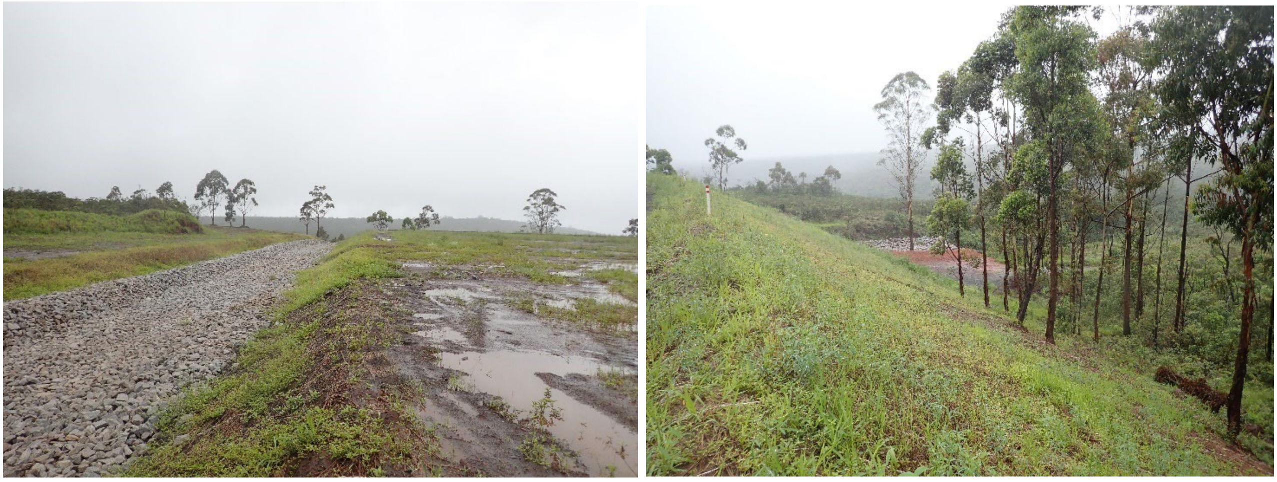
The dyke was constructed some time before 2006, however, the exact date is unknown. Operational changes resulted in most of the generated sediments being retained inside the open pit and the dyke was no longer necessary. The structure was decommissioned in 2019, and closure was accepted by the Minas Gerais state environmental agency, Fundação Estadual Do Meio Ambiente (FEAM), in 2020 despite having a large sump and area of exposed unconsolidated sediments at the upstream limit. Due to decommissioning, Cobras is not classified under ANM Resolution 95/2022.

2.2.1.1 Dam safety condition

The decommissioning project regraded the surface of the sediments retained behind the dyke with a 1% slope toward the perimeter channel on left flank of the basin that passes through the left abutment of the embankment (Figure 1). During the initial site visit it was observed that surface settlement had resulted in ponding and therefore increased infiltration.

Upon commencing the audits, the dam had no instrumentation to record the phreatic level within the dam or track deformation trends. Through discussions it was also determined that the spillway design and construction did not consider the potential for erosion of the weathered rock profile below the erosion protection forming the spillway invert.

Reported stability analyses for the decommissioned dyke demonstrated adequate global slope stability despite the relatively steep downstream slope inclination. SLR carried out independent checks and determined a lower than desired safety factor with a reduced angle of internal friction indicating the potential for shallow slumping that could lead to and erosion and dam instability. Deeper slip surfaces appeared to have adequate safety factors.



(a) (b)

Figure 1 December 3, 2019 photographs of Cobras Dam. (a) Surface ponding and rock lined channel at left flank / dam abutment; (b) Downstream slope of the dam and spillway chute in background

2.2.1.2 Risk reduction measures

Credible failure modes identified include:

- spillway channel erosion leading to abutment and dam slope instability,
- slope instability due to lower than expected fill shear strength, and
- overtopping during the design flood generated from the probable maximum precipitation.

SLR recommended that Vale update the stability analysis considering the lower friction angle and reduced apparent cohesion values, and consider a downstream slope with a flatter gradient to reduce the risk with respect to long term, progressive and erosional failures on the slope, and reduce maintenance requirements.

In 2022, Vale installed four piezometers in the Cobras structure, with three piezometers in the dam fill and one in the foundation. Piezometric data has not been evaluated by SLR to determine if additional instruments should be installed.

2.3 Risk considerations for evaluating alternatives (group 2)

Arriving at the optimal closure solution benefits from an evaluation of alternatives based on technical data and an assessment of risks associated during construction and in the longer term. A poor understanding of the dam design and construction and/or other data limitations requires that the design assumptions be proved out in the field and could lead to unsafe conditions, schedule delays or cost overruns. That said, construction execution plans that provide flexibility to manage changed conditions are advantageous.

The Paracutu Dam and Auxilary Dyke removal provide useful examples of these considerations.

2.3.1 Paracatu

Paracatu Dam was constructed to retain sediments generated in the São Luiz Mine and was originally designed and constructed by the mine operations team without the use of geotechnical, geological, and hydraulic studies. The dyke was constructed some time before 2008, however, the exact date is unknown. The dam had 22 m maximum height, 90 m crest length, a catchment of 38 ha and impounded 13,400 m^3. The dam was originally constructed as a single stage embankment. A downstream rock buttress, internal drainage system and spillway were implemented in 2010.

The initial audits by SLR determined the dam fill and foundation characterization were poorly understood and recommended further geotechnical investigations to clarify uncertainties with regard to slope stability. The spillway was also determined to have inadequate capacity to safely pass the design storm with adequate freeboard by the newly appointed Engineer of Record.

The dam condition at the start of the audit program is shown on Figure 2(a).

2.3.1.1 Options considered

Vale considered two closure options: partial dam removal, and complete dam removal. For the comparison Vale considered that partial dam removal and a flatter slope reasonably mitigated the dam safety issues associated with poor dam design and construction stewardship, and anomalous dam behaviours such as cracking observed on the slopes, foregoing the need for additional geotechnical investigations.

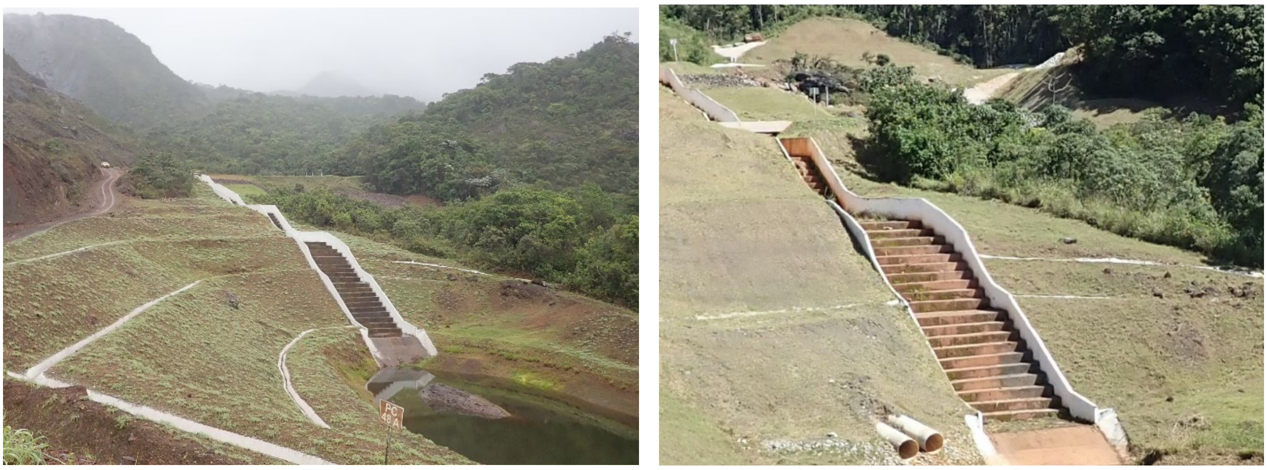
Vale intended to upgrade the spillway to increase the capacity to safely pass the design storm with a bypass pumping system to mitigate overtopping risks temporarily while a spillway improvement design was developed. Rather, Vale decided to build a secondary spillway in the right abutment to provide passive drainage and reduce maintenance relative to the high pumping rate and active operation of a pumping system.

2.3.1.2 Adopted closure scenario

Vale installed the twin pipelines comprising the secondary spillway evident on Figure 2(b), however construction challenges related to the steep terrain and deficiencies with adequate pipe bedding and cover compaction meant several dam safety issues were raised including potential pipe failure leading to erosion and failure of the dam. Additionally, a portion of the upstream slope slumped after Vale excavated the sediments upstream of the dam and abrupt piezometric responses in the dam were observed following a storm and a rapid pond level increase suggesting the presence of construction defects. Vale quickly constructed a low permeability soil cover on the upstream dam slope to impede further flow into the dam and no serious consequences occurred.

Considering the secondary spillway pipeline dam safety issues, poor dam design and construction stewardship, Vale elected to remove the dam completely and control surface runoff with an excavated sediment pond and concrete drainage channel. Precipitation runoff from the upstream catchment flows through a sediment pond excavated in the natural ground upstream of the former dam location and discharges into a reinforced concrete channel and reports to the original energy dissipation basin. This example illustrates the benefit of adequate geotechnical characterization and dam design stewardship in the decision process.

Figure 2(b) shows the dam structure has been completely removed. No credible failure modes have been identified for the decharacterized structure.



(a) (b)

Figure 2 Photographs of Paracatu Dam. (a) Original condition, December 3, 2019; (b) After dam removal May 2, 2023. Note the two buried pipes near the stepped spillway chute.

2.3.2 Auxiliary dyke

Vale acquired Águas Claras Mine from Minerações Brasileiras Reunidas (MBR) in 2007 at which time Dam 5 and the Auxiliary Dyke were already in operation. Dam 5 was built in two stages for tailings containment and water supply to the processing plant. In 1973 the starter dam was built approximately 47.5 m high (Elev. 889.5 m) using soil and rock and an upstream compacted clay zone. In 1978, a downstream raise was constructed to maximum height of 79.2 m (Elev. 921.2 m) with compacted soil (saprolite) and the upstream clay layer was extended to the crest. To increase the tailings storage capacity the Auxiliary Dyke was constructed in the Dam 5 impoundment approximately 350 m upstream of Dam 5, effectively forming an upper terrace. The Auxiliary Dyke was constructed in three stages from 1989 to 1991. The initial 2 m raise above the tailings elevation to a crest elevation of 920 m in 1990 with subsequent dyke raises of 2.5 m in the centerline manner (to Elev. 922.5 m), and 4 m in 1991 as an upstream raise (to Elev. 926.5 m). Finally, a 2 m high gabion wall was added to the crest in 2000 (to Elev. 928.5 m).

Dam 5 has not received tailings since mine operations ended. Since 2002, the dam has only been used for sediment containment. In 2019, Auxiliar Dyke was classified as an upstream raise and Vale began planning removal.

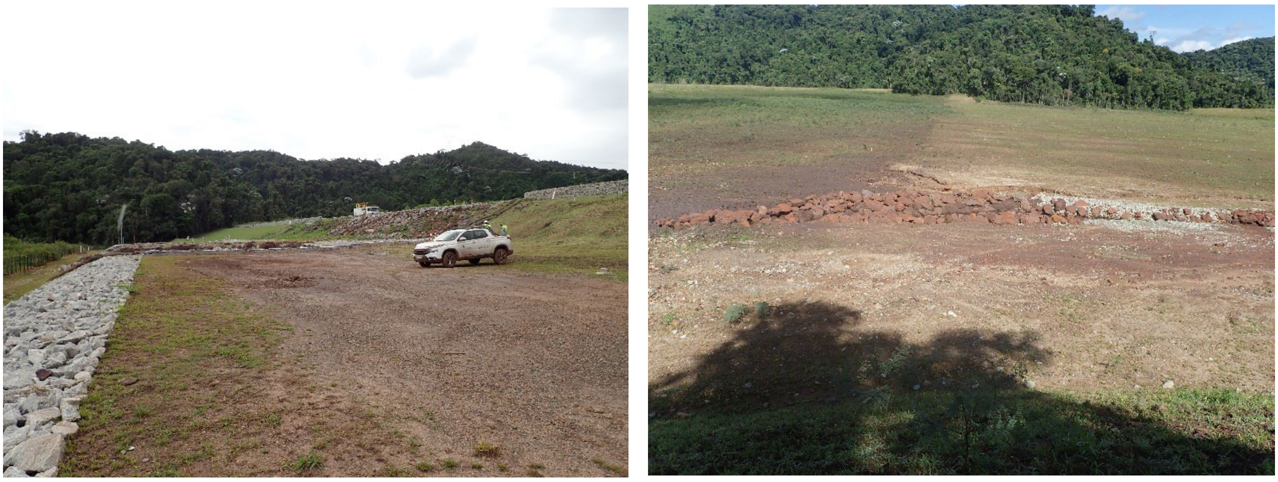
Figure 3(a) shows the Auxilary Dyke in 2021.

2.3.2.1 Options considered

As an upstream raise, the only option for Auxiliary Dyke closure was full removal. The closure design comprised excavating tailings from upstream of the Auxiliary Dyke, placing the excavated tailings downstream of the Auxiliary Dyke and removing most of the Auxiliary Dyke fill to create a 4% slope from upstream to downstream.

Vale considered several alternatives for closure construction execution that mostly centred around tailings dewatering and water management: dewater the tailings upstream of the Auxiliary Dyke using vacuum well points with tailings excavation in panels, and lowering the water table using a series of deep and shallow ditches then excavating tailings in shallow panels using amphibious excavators. A series of tests to evaluate vacuum well efficiency produced poor results, and the ditching option was selected.

Regardless of the execution option, Vale constructed a 7 m high (Elev. 927 m) gabion wall on the crest of Dam 5 to protect against potential overtopping in the event of an Auxiliary Dyke failure and tailings mobilization. Tailings removal commenced only after the gabion wall construction was complete.

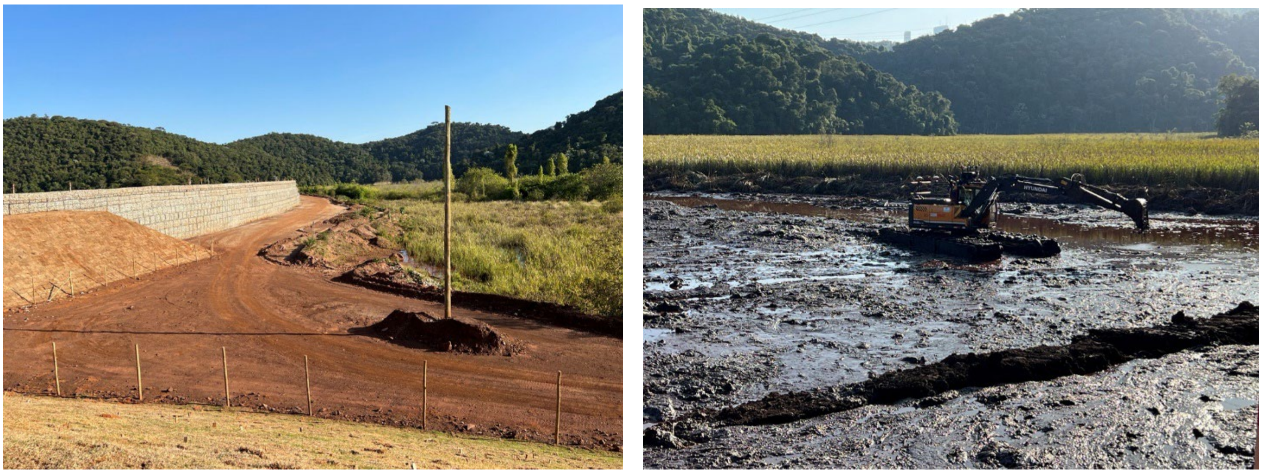


(a) (b)

Figure 3 Photographs of MAC B5 Auxilary Dyke. (a) Original condition, November 19, 2021 with lower upper terrace at the right; (b) Sloping tailings surface and drainage swale April 17, 2023.

2.3.2.2 Adopted closure scenario

Upon commencing closure construction, Vale experienced difficulty lowering the water table in the tailings and managing water within the tailings excavation area which inhibited excavator movement. Vale continued to maintain deep ditches upstream of the excavation area and along the left margin of the impoundment, but the shallow ditches were not constructed, and ballast was used to support truck movement closer to the excavation area. Due to the inability to place and compact saturated tailings, imported soil was used to complete the downstream fill section. This example highlights the benefit of options studies and maintaining flexibility and contingencies when developing the construction execution plans.



(a) (b)

Figure 4 Photographs of MAC (a) Gabion wall on Dam 5 crest, May 30, 2022; (b) Challenges moving amphibious excavator upstream of Auxilary Dyke due to saturated tailings, May 30, 2022.

Vale is currently investigating the potential risks associated with cyclic mobility of the sloping tailings surface during an earthquake and may decide to leave a portion of the gabion wall on the crest of Dam 5 to prevent the possibility of overtopping by mobilized tailings. No other credible failure modes have been identified for the closed Auxiliary Dyke.

2.4 Management of risks during closure construction (group 3)

Comprehensive closure planning is critical for high risk dams susceptible to credible failure modes that could be triggered by the construction activities, and a sound understanding of the dam design basis and performance is fundamental to good decision making.

2.4.1 Fernandinho

Vale acquired the Abóboras Mine in 2007 from MBR at which time the Fernandinho Dam was in operation. Fernandinho was constructed in a mined out open pit in 2006 and was raised upstream above the pit rim over several years. Fernandinho was 130 m long dam that had a maximum height of 19 m (Elev. 1302.5 m). When SLR commenced the audits Fernandinho was observed to be performing satisfactorily with no significant safety issues noted. Vale removed the Fernandinho Dam in 2021, rehabilitated the pit slopes and revegetated the remaining tailings area.

2.4.1.1 Safety concerns during construction

Construction execution planning for Fernandinho closure considered the possibility of tailings liquefaction induced by construction equipment vibrations, with a higher risk near the dam. Vale conducted a vibration test on the Fernandinho tailings several hundred meters upstream of the dam to measure peak particle velocities and induced porewater pressures. The phreatic level in the Fernandinho Dam and tailings was sufficiently deep that no significant risks were identified with the induced vibrations. However, vibration test results were evaluated and standoff distances from the dam crest were set as a precaution.

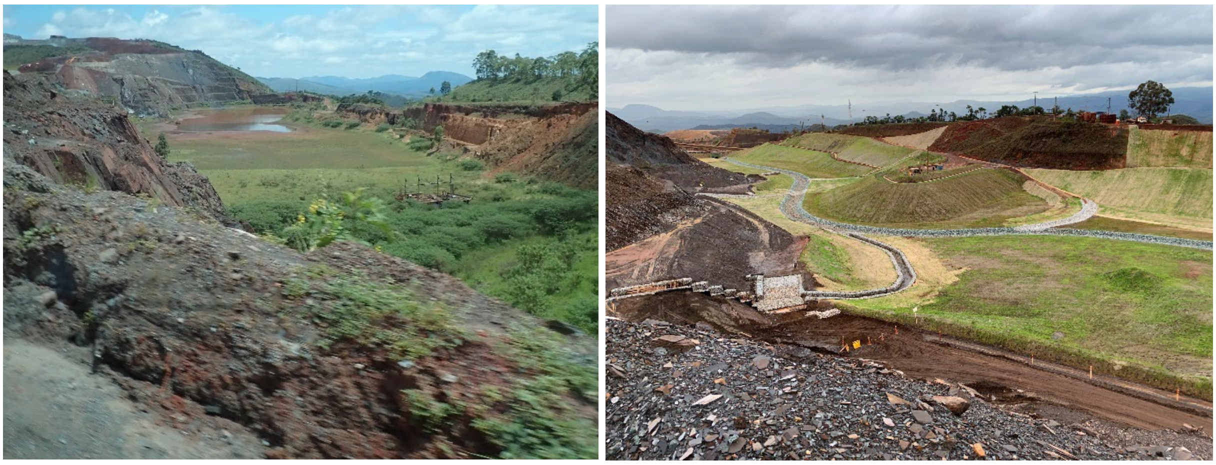
Vibration tests were also carried out near Vargem Grande Dam which is along the haulage route utilized for the tailings spoil transport to ensure no impacts were imparted on this adjacent dam. The tests measured vibrations near background levels at Vargem Grande.

2.4.1.2 Risk mitigation measures and progress

Fernandinho closure construction was completed in 2021 including full removal of the dam, construction of a central drainage channel, and vegetation of the tailings surface and basin (former pit wall) slopes.

No significant construction monitoring activities were required because the dam had a low phreatic level and no significant pond. Tailings were excavated and hauled to mined out open pits. The central channel over the remaining tailings was designed to convey the 10,000-year flood with energy-dissipation prior to entry into the mined-out open pit located downstream. Design considerations included stabilization of the impoundment rim slopes after tailings removal, the stability on adjacent mine infrastructure and buildings, water management and revegetation.

Vibration levels at the adjacent Vargem Grande Dam were measured as part of routine dam surveillance and no significant safety issues were noted.



(a) (b)

Figure 5 Photographs of Fernandinho. (a) Prior to closure, January 15, 2020; (b) Advanced closure implementation, November 19, 2021.

2.4.2 Vargem Grande

Vargem Grande was in operation when Vale acquired Abóboras in 2007. Tailings deposition into Vargem Grande ceased in 2008, after which time it was utilized as a water reservoir until 2019 when the site was interdicted by ANM. The Vargem Grande Dam is about 884 m long and has a maximum height of between 35 and 40 m (Elev. 1307 m). Vargem Grande is classified as a high risk, high damage potential dam due to the impounded volume (9.5 Mm^3), proximity to communities and infrastructure, and potential environmental damage.

Vargem Grande is currently at Emergency Level 1 because of susceptibility of failure due to tailings liquefaction. Since 2019, Vale has conducted continuous improvements to the dam including pumping out the pond, reconstitution of the foundation drainage outlet, surface drainage improvements and installation of sediment control measures. Channels have been cut into the tailings to better manage drainage from the beaches and from within the upper tailings.

Due to the upstream construction, the Vargem Grande Dam raises will be removed. Vale began mass tailings excavation in 2022. The work is scheduled to take approximately 5 years after which time the starter dam will remain in place for sediment control.

2.4.2.1 Safety concerns during construction

Safety concerns during closure construction include dam slope instability due to tailings liquefaction or softening due to induced vibrations or high water levels. The relatively complex dam foundation conditions that have been approached differently by various reviewers, auditors and designers has resulted in various opinions of the dam safety conditions. Similarly, poor installation of dam instrumentation and a lack of stewardship of the data obtained has resulted in uncertainty regarding stability.

The stability assessment has improved with a better understanding of the phreatic level obtained after installing new piezometers. The safety factor values calculated for slip surfaces within the tailings are now marginally less than the required minimum for static loading conditions. Vale and the Engineer of Record were able to establish a stable, phreatic level since installing a series of electric piezometers with proper surface seals. Improved geotechnical characterization has increased confidence in planning for closure.

Existing dam instrumentation has been used to establish background phreatic and vibration levels as part of the routine dam safety surveillance program.

As part of the improved drainage works the spillway invert was lowered and appears to be adequately sized to pass the design flood resulting from the PMP.

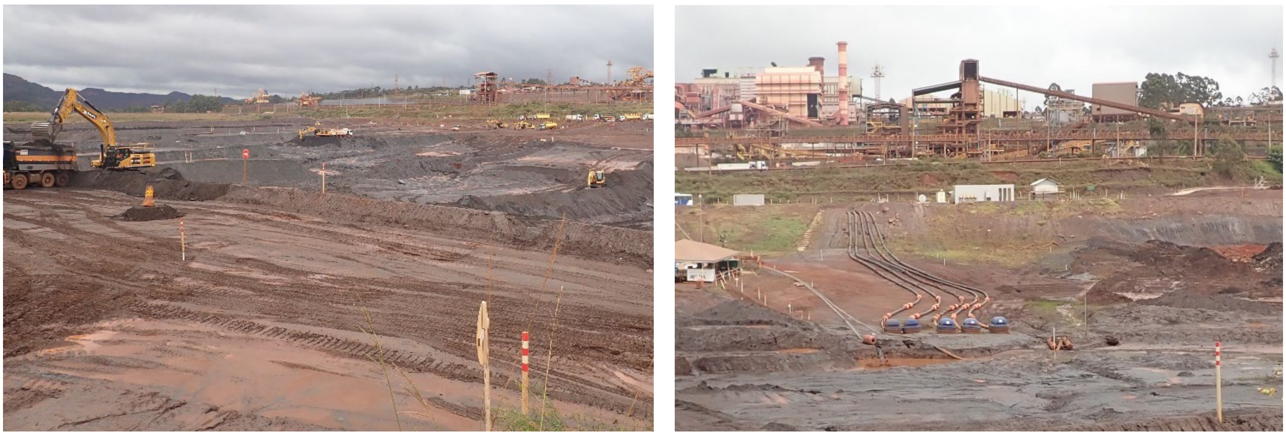
2.4.2.2 Risk mitigation measures and progress

Vale has adopted a pragmatic approach to excavating the tailings progressively, starting from the upstream side of the basin and working towards the dam in order to take advantage of experience that will be gained through the work to minimize risk.

Based on lessons learned from Fernandinho, channel excavation and lowering of the water table before excavating the partially drained tailings are being implemented successfully. A sump was established in natural ground prior to commencing significant tailings excavation. Drainage channels discharging to the sump are completed in a grid fashion prior to commencing tailings excavation (Figure 6). The water level is maintained approximately 5.5 m below working tailings and drains readily to the sump which is about 3 m lower.

Safe limits have been set for the overall slope height and inclination to limit shearing and strain within the tailings to mitigate static liquefaction concerns.

Vale conducted a construction equipment vibration test on the Vargem Grande tailings to mitigate liquefaction risks and are currently working to establish vibration monitoring between the work area and the dam to improve vibration attenuation relationships in order to allow for possible future optimization. Lowering the phreatic level significantly below the working tailings surface has served to reduce the risk associated with construction induced vibrations.



(a) (b)

Figure 6 Photographs of Vargem Grande, April 19, 2023 (a) Low drainage channels allow excavation of drained tailings; (b) The operational sump level at elevation 1,293 m is approximately 9 m below the working tailings surface, and standby pumps ready for the rainy season.

2.4.3 B3/B4

B3/B4 has been classified as a high damage potential, high risk tailings impoundment dam with a maximum height of about 55 m and crest length 210 m. The dam contains tailings and/or sediment with an impounded volume in the order of 2.7 Mm^3. A mine waste stockpile (PDE X) is located in the upstream region of the B3/B4 tailings impoundment. A second mine waste stockpile (PDE Oeste) is present above the right abutment. The cross-sectional geometry of B3/B4 has been inferred from boreholes put down for As-Is reporting and routine dam safety assessments.

There are no active operations at B3/B4 other than monitoring and surveillance, maintenance, and closure activities that commenced in late 2020.

The dam was at Emergency Level 3 because the static slope stability requirements are not satisfied, and the retained solids are in a contractive state and therefore prone to static and dynamic (seismic) liquefaction.

The emergency spillway is also not sufficient to protect the dam by safely passing runoff from extreme storm events.

At this time, the dam appears to be stable and no significant deformation trends have been noted in routine surveillance inspections or through dam instrumentation and there are no indications of imminent failure. A watershed diversion channel was completed in 2019 at the right flank of the facility (Figure 4) to reduce the runoff inflow to the B3/B4 pond. Vale has lowered the pond significantly and sufficient installed pumping capacity can maintain the pond below the spillway invert except in extreme storm conditions. Three deep dewatering wells were installed in the right flank of the impoundment in 2019, however these have not been effective in terms of lowering the phreatic level in the tailings significantly.

2.4.3.1 Safety concerns during construction

The primary risk considerations for implementing closure are water management and limiting construction induced vibrations and shearing that could trigger tailings liquefaction. The spillway appears to be of reasonable size to pass the design storm, however, spillway failure is considered to be a credible failure mode because the erosion protection is not considered to be adequate. The excavation has been planned to facilitate storing the storm runoff within the excavation.

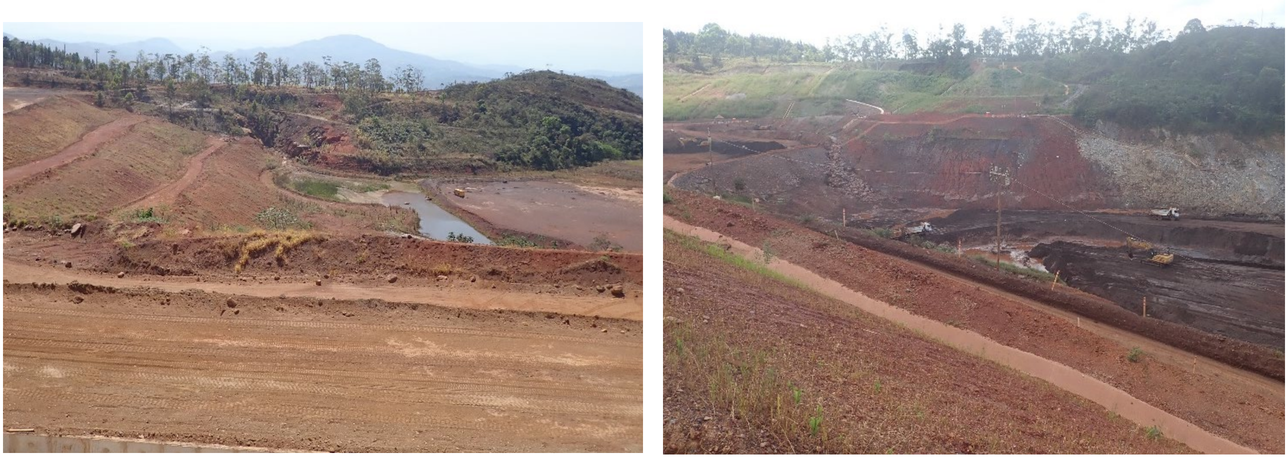
2.4.3.2 Risk mitigation measures and progress

Prior to commencing any excavation Vale constructed a rockfill backup dam approximately 10 km downstream of B3/B4 that provides adequate storage to contain a total release of the B3/B4 tailings, the dam fill, and a portion of PDE X along with storm runoff reporting with the released tailings. Citizens within the potential inundation zone were evacuated and work on the dam and within the potential inundation zone is performed using remotely operated equipment. In this sense the work did not proceed until there was no risk to citizens or workers.

The decommissioning plan involves removal of B3/B4 and the upstream tailings slowly in stages so as to avoid triggering liquefaction. The initial works involved removing a portion of PDE X to expose natural ground (weathered rock) at the toe of the stockpile thereby creating a separation between the tailings and mine waste.

Maximum slope height and inclination limits have been set for excavation in the tailings to limit shearing risk, and instrumentation has been installed in the dams and around the perimeter of the tailings to measure the vibration levels induced by the construction equipment to mitigate liquefaction risks. The current dam instrumentation is appropriate for detecting conditions that could lead to the failure modes identified, except seismic liquefaction. Diversion channel and PDE Oeste slope inspections are carried out to identify concerns related to slope instability and ditch blockage, particularly in the rainy season.

Approximately 2/3 of the decharacterization work has been safely completed to date. Detailed stress-strain modelling is being performed by consultants to Vale in order to optimize the later stages of the excavation planning in the narrower portions of the valley.



(a) (b)

Figure 7 Photographs of B3/B4. (a) PDE X and pond, September 23, 2019; (b) Sump located near original ground level, PDE X, and depth of tailings removal on the left flank, April 18, 2023.

3 Discussion

The case studies highlight the need to maintain a long-term perspective, consider a range of alternatives, and maintain flexibility to manage dam closure risks considering knowledge and data gaps. All dam closure planning needs to consider the level of confidence in terms of understanding the dam design basis and performance. Risk assessments are recommended to identify design and construction execution risks during the planning phase. Contingency planning should address known risks prior to starting closure construction to facilitate quick responses and limited impacts to dam safety, worker safety and schedules.

For upstream raised dams constructed on contractile tailings or dams with other significant inherent risks, construction planning should be practical, methodical, and flexible. Dam instrumentation and data quality are paramount to ensure safety. Effective monitoring plans should take into account the loss and replacement of dam monitoring instruments as construction activities move locations and the risks change.

The regulatory requirements for closure of mining (tailings) dams in Brazil generally consist of the mining proponent submitting a closure plan outlining the dam characteristics, operational history, closure, and rehabilitation measures proposed, and the monitoring associated with such, albeit for a relatively short period. Corporate governance such as adopted by Vale and the principles outlined in PRI et al. (2020) and ICMM (2021) are considered to be necessary to mitigate long-term risks.

4 References

CDA 2013, Dam Safety Guidelines 2007 (2013 Edition), Canadian Dam Association,2013.

CDA 2019, *Application of Dam Safety Guidelines to Mining Dams 2014 (2019 Edition)*, *Technical Bulletin by the* Canadian Dam Association, 2019.

ICMM, 2021, Tailings Management – A Good Practice Guide, International Council on Mining & Metals, May, 2021.

PRI et al. 2020. Global Industry Standard on Tailings Management, Principles for Responsible Investment, International Council on Mining & Metals & UN Environment Programme, August, 2020.