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Low-disturbance decharacterisation of a legacy bauxite tailings facility in the Brazilian Amazon: integrated drainage, revegetation and monitoring

Nathalia Marques da Silva [a,*], Marcelo Carvalho Mollica [a]

[a] *Mineração Rio do Norte, Brazil*

Abstract

The SP-2/3 bauxite tailings storage facility is part of a 1,405 ha tailings disposal system on a plateau in the Brazilian Amazon, planned for progressive, integrated closure of its structure to restore land function and reintegrate the plateau landform. Constructed in 1988 for deposition of thickened tailings, SP-2/3 operated until 2000 when it became inactive and then the natural recovery process began, during a period of limited Brazilian requirements for dam decharacterisation. After approximately 20 years of rehabilitation and ecological re-establishment, it was necessary to develop a closure strategy aligned with Brazilian dam decharacterisation requirements (including ANM Resolution No. 95) and with international best practices, such as the Global Industry Standard on Tailings Management (GISTM), while preserving established vegetation and minimising disturbance to the tailings surface.

This paper presents a low-disturbance closure approach based on integrated engineering and environmental analysis to reinstate surface drainage, eliminate persistent ponding and support long-term revegetation, while reducing residual geotechnical and environmental risks. Works comprised localised openings through major internal topographic barriers to restore hydraulic connectivity, spillways to provide compliant overflow capacity, and localised fills in internal depressions previously prone to ponding to route stormwater to designed drainage pathways. Revegetation protocols were adapted to site conditions using selective topsoil placement, enrichment techniques and treatments for areas formerly affected by waterlogging.

Two years of post-construction monitoring confirmed the efficiency of the drainage system, the proper performance of spillways during rainfall events, the stability of reshaped surface, and the continued improvement in vegetation cover. Pre- and post-intervention comparisons demonstrate significant progress in vegetation recovery at SP-2/3 while retaining most pre-existing vegetation. Revegetation included the planting of 19,914 individuals across 18 native tree species. The outcomes demonstrate that integrating terrain morphology, infiltration and water accumulation processes, and environmental criteria from project inception can enable low-disturbance decharacterisation of legacy tailings facilities in environmentally sensitive settings.

Keywords: *mine closure, decharacterisation, bauxite tailings, low-disturbance closure, surface drainage, revegetation, post-closure monitoring, Brazilian Amazon*

1 Introduction

Legacy tailings facilities constructed prior to the establishment of modern closure and decharacterisation requirements present a significant technical and environmental challenge for the mining industry. In Brazil, the evolution of the regulatory framework – particularly the introduction of mandatory decharacterisation requirements under ANM Resolution No. 95 (ANM 2022) – has increased expectations regarding the management of residual geotechnical and environmental risks associated with inactive tailings structures.

* Corresponding author. Email address: nathalia.silva@mrn.com.br

According to ANM Resolution No. 95 (ANM 2022), dam decharacterisation is achieved when a former tailings dam no longer performs the function of retaining tailings or water and can be managed as a reclaimed landform. Although the term ‘decharacterisation’ is specific to the Brazilian regulatory framework, similar concepts internationally are generally associated with mine closure, transition to a stable landform, dam removal or elimination of dam safety risk.

In parallel, international initiatives such as the Global Industry Standard on Tailings Management (GISTM 2020) have reinforced the need for integrated, risk-based approaches throughout the full life cycle of tailings facilities, including closure and post-closure phases. These frameworks emphasise the importance of eliminating or reducing residual risks while ensuring long-term physical stability, environmental protection and alignment with surrounding ecosystems.

For legacy facilities located in environmentally sensitive settings, conventional closure strategies based on large-scale surface regrading or extensive earthworks may conflict with ecological objectives, particularly where natural recovery and vegetation re-establishment have already occurred. In such contexts, closure solutions must reconcile modern regulatory requirements with the preservation of existing vegetation and the minimisation of disturbance to the tailings surface.

The SP-2/3 bauxite tailings storage facility, located on a plateau within the Brazilian Amazon, represents a typical example of this challenge. Following approximately 20 years of natural recovery after termination of operations, the facility exhibited substantial vegetation cover, while localised morphological and drainage-related constraints continued to influence surface water behaviour and revegetation performance in specific areas.

This paper presents a diagnostic-based, low-disturbance decharacterisation approach, developed through integrated geotechnical, hydraulic and environmental assessments, to address these challenges at SP-2/3. The proposed strategy focuses on restoring surface drainage connectivity, managing localised water accumulation and supporting long-term ecological recovery, while avoiding extensive internal remobilisation of tailings. The approach demonstrates how legacy tailings facilities in sensitive environments can be decharacterised in compliance with modern regulatory and international standards through targeted, evidence-based interventions.

2 Location and study area context

Mineração Rio do Norte (MRN) operates within a sustainable use conservation unit, the Saracá-Taquera National Forest (FLONA), located in the Brazilian Amazon. The SP-2/3 bauxite tailings storage facility forms part of an integrated tailings disposal system covering approximately 1,405 ha, situated on a plateau characterised by sensitive environmental conditions and high ecological value (Figure 1).

The SP-2/3 facility, covering approximately 78 ha, was constructed in 1988 to receive thickened bauxite tailings and remained operational until 2000, when deposition activities ceased. Following decommissioning, natural recovery and revegetation processes were initiated during a period in which Brazilian regulatory requirements for tailings dam decharacterisation were still limited. Over the subsequent 2 decades, significant ecological re-establishment occurred across most of the facility, resulting in widespread vegetation cover on the tailings surface.

Despite this overall recovery, field inspections and site observations identified localised areas within the facility where vegetation development remained limited. These areas were spatially correlated with surface depressions and irregular topography, which promoted persistent water accumulation (ponding). These surface irregularities were associated with long-term consolidation and settlement processes of the tailings mass, driven by self-weight consolidation over approximately 20 years.

Given the presence of these localised constraints to revegetation and the evolution of Brazilian regulatory requirements, a closure strategy was developed in 2022 to enable full decharacterisation of the facility. The strategy was designed to comply with applicable Brazilian technical standards, and international best practices, including the GISTM (GISTM 2020), while prioritising the preservation of established vegetation and the minimisation of disturbance to the surface.

This context provided the basis for a diagnostic-led, low-disturbance closure approach focused on restoring surface drainage connectivity, managing localised water accumulation, and supporting long-term ecological recovery, as described in the following sections.

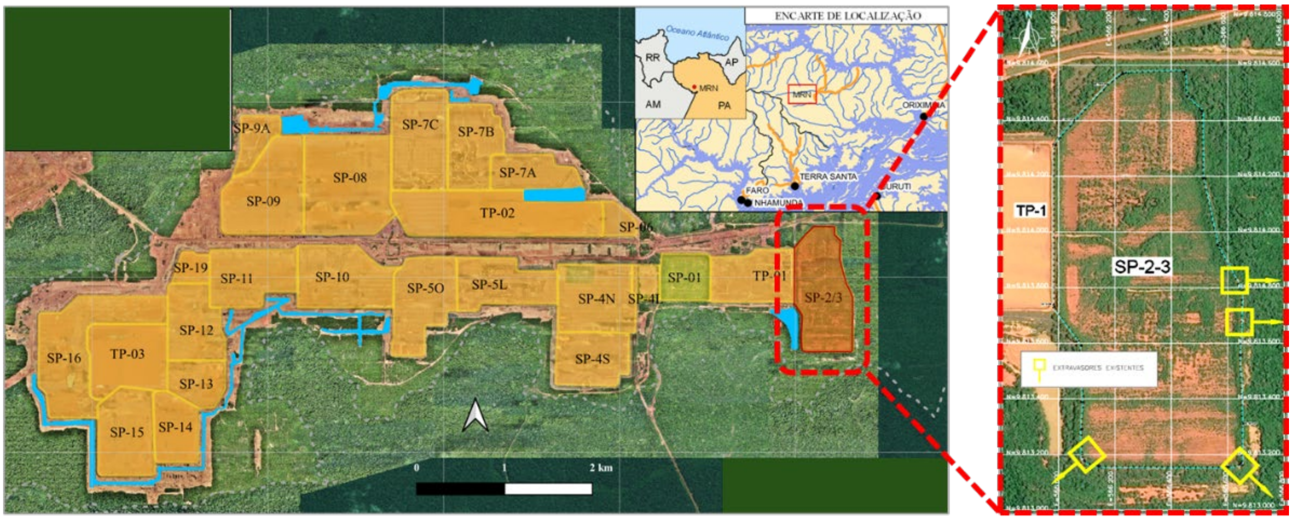


Figure 1 (a) Location of the study area; (b) Enlarged view of study area

3 Methodology and diagnostic assessment

3.1 Geotechnical investigation and settlement assessment

A geotechnical investigation campaign was undertaken in 2020 to support the diagnostic assessment of the deposited tailings and to inform low-disturbance closure decisions. The investigation included standard penetration test (SPT) soundings, sampling to determine solids content profiles with depth, and nine cone penetrometer with pore pressure measurement (CPTu) tests, 5 of which were performed within the impoundment footprint (Figure 2).

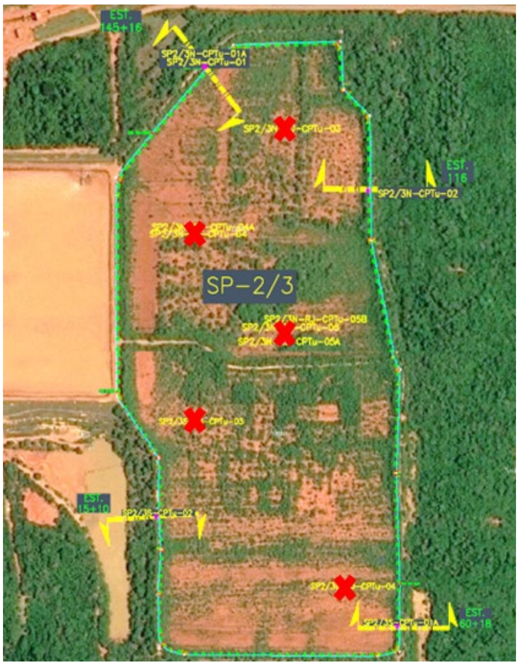


Figure 2 Location of the CPTu tests within the impoundment

Solids content profiles indicated values predominantly of 60–70%, without a strong systematic trend with depth. This behaviour suggests that the deposit had already reached an advanced state of consolidation following more than 20 years of inactivity after deposition ceased. Slightly higher solids contents (approaching 67%) observed in the shallow portion of the deposit are interpreted as the result of long-term desiccation processes, including evaporation and vegetation-driven evapotranspiration. Similar behaviour has been reported for fine bauxite tailings exposed to prolonged drying conditions, where desiccation can promote progressive moisture loss in near-surface layers (Feijó et al. 2025).

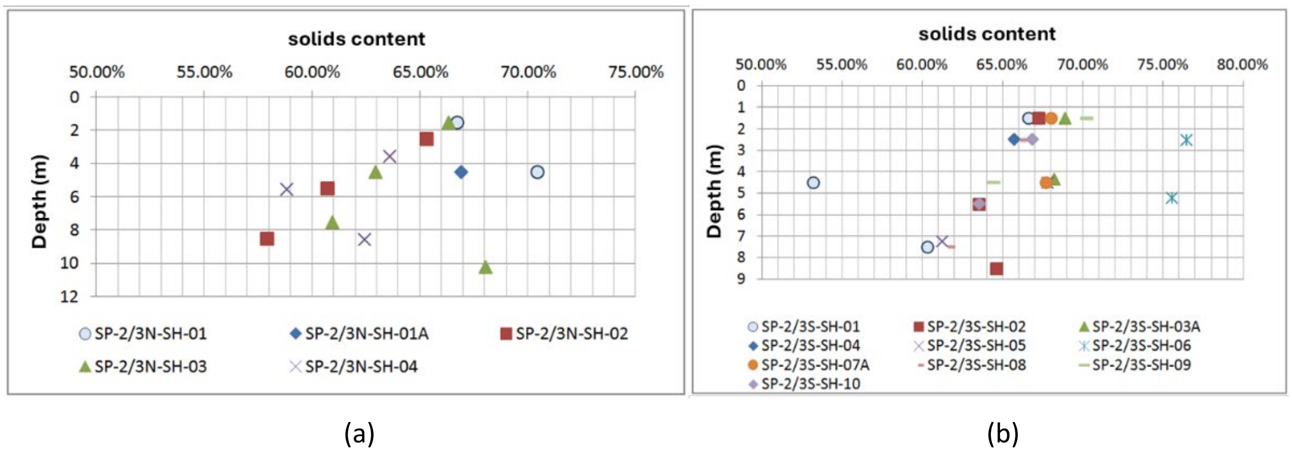


Figure 3 Solids content profile; (a) Data from northern sector; (b) Data from southern sector

CPTu results with dissipation testing were used to evaluate the tailings consolidation state and potential for long-term settlement. Cone tip resistance within the tailings layer was predominantly below ~750 kPa. Dissipation behaviour interpreted using the t50 parameter indicated rapid pore pressure dissipation, with excess pore pressures approaching zero at the tested locations. Figure 4 illustrates a representative result from CPTu testing, whereas Figure 5 presents one of the dissipation tests carried out in the tailings layer. This behaviour is consistent with the absence of persistent internal flow conditions that would indicate a stable phreatic surface within the impoundment. The results indicate that self-weight consolidation had largely occurred by the time of design, providing confidence in long-term surface stability and supporting the adoption of decharacterisation solutions based on low-disturbance interventions with minimal internal remobilisation of tailings.

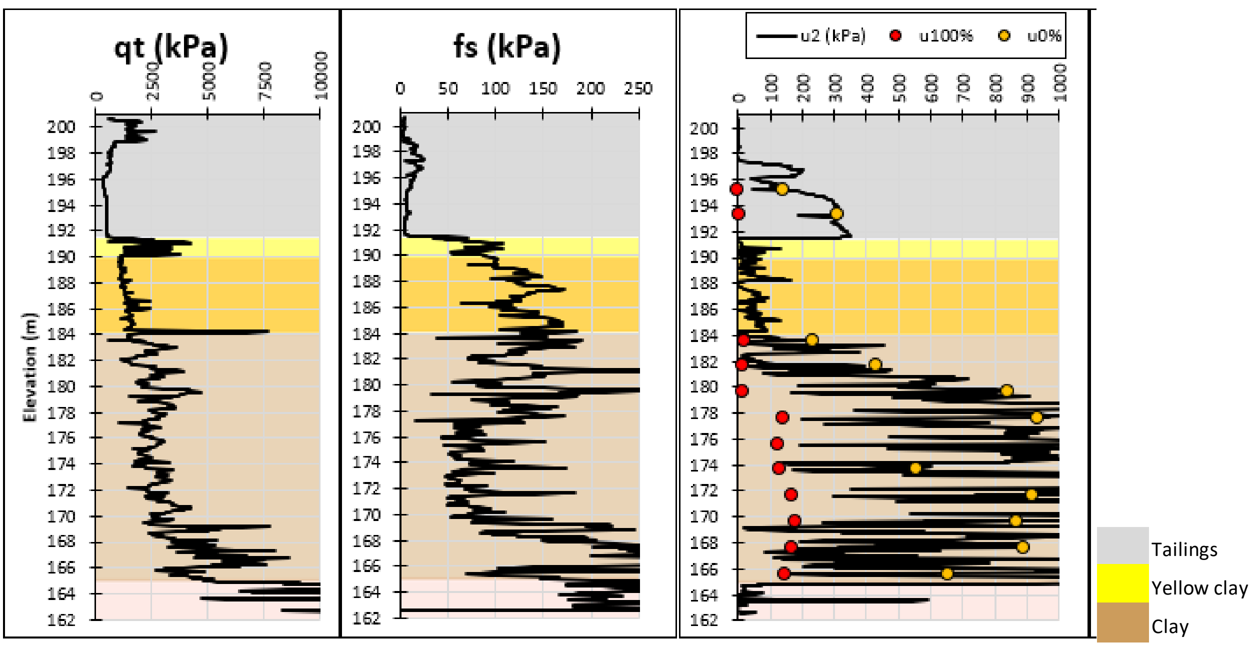


Figure 4 CPTu test results obtained within the tailings impoundment

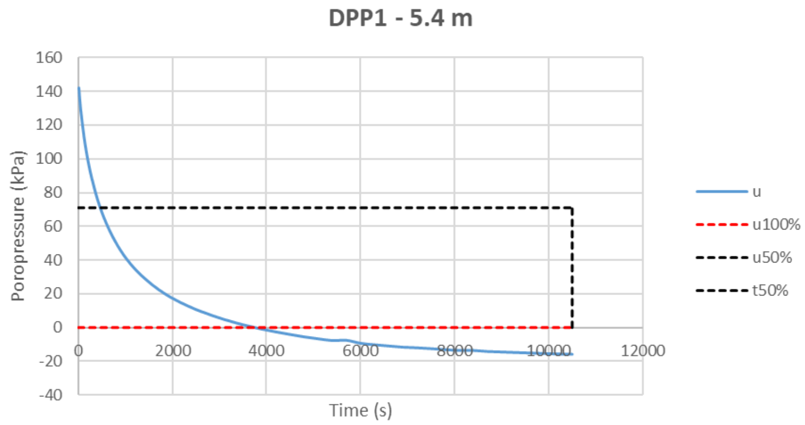
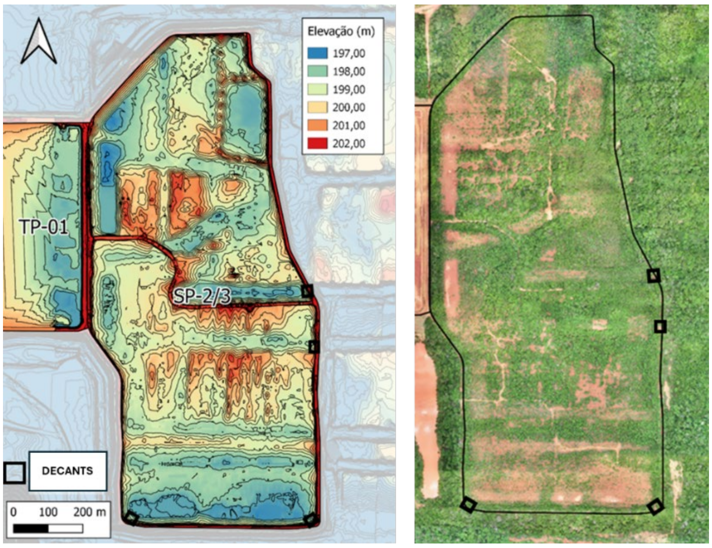


Figure 5 Dissipation test result obtained within the tailings impoundment

3.2 Topographic assessment and identification of ponding controls

A detailed topographic survey and surface mapping were conducted to characterise the tailings surface morphology and identify drivers of persistent water accumulation. The assessment confirmed that the impoundment surface exhibits irregular topography, including local depressions and internal topographic barriers. These features were interpreted as the result of long-term settlement and consolidation processes acting over approximately 2 decades following cessation of deposition.

Spatial comparison between the elevation model and field observations indicated a consistent pattern: areas with well-developed vegetation were generally associated with higher elevations, whereas areas with limited vegetation performance coincided with lower-lying zones and depressions prone to persistent ponding (Figure 6). Although no specific eco-physiological assessment was conducted, field observations from revegetation programs implemented over several years in bauxite tailings areas indicate that prolonged waterlogging may limit vegetation establishment and development in such environments. Potential mechanisms include reduced oxygen availability within the root zone, decreased plant growth, partial mortality of fine roots, and increased susceptibility to phytopathogens under prolonged saturated conditions. In addition, revegetation efforts were focused on native Amazonian species consistent with the target ecosystem, limiting the selection of species naturally adapted to persistently flooded conditions. These observations supported the interpretation that persistent surface ponding was an important factor affecting revegetation performance and should be addressed as part of the closure strategy.



(a) (b)

Figure 6 (a) Surface elevation model; (b) Vegetation cover observed in the 2022 orthophoto

The diagnostic evaluation further indicated that the irregular surface and internal barriers constrained overland flow routing, reducing hydraulic connectivity between ponded areas and existing overflow routes. Consequently, surface run-off generated within the impoundment did not reliably contribute to overflow structures under rainfall events. This finding directly supported the closure concept by establishing the need for targeted, low-disturbance interventions to reinstate surface drainage connectivity – through localised openings and defined flow paths – so that stormwater could be conveyed from internally ponded zones towards the designed overflow discharge points.

Figure 7, obtained prior to the closure interventions, shows an irregular surface with internal topographic barriers that restricted surface run-off toward the overflow structures, which were also associated with areas of limited vegetation cover.

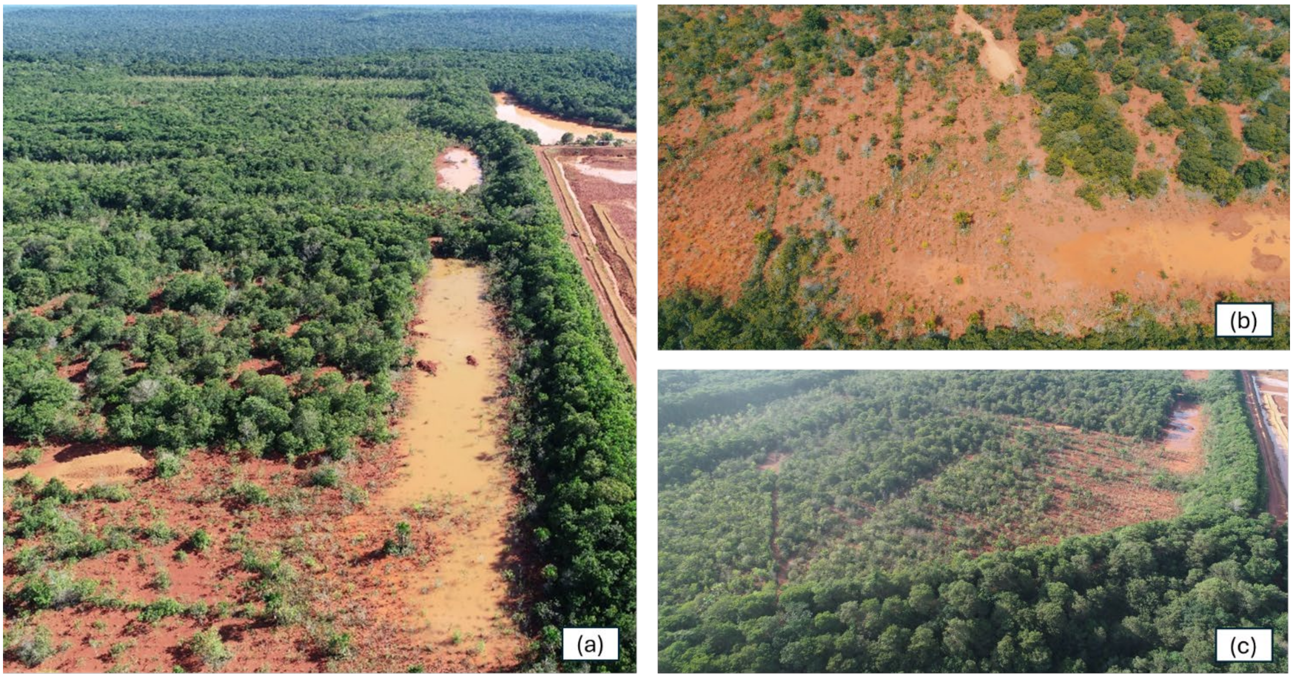


Figure 7 (a) Areas with water accumulation and internal topographic barriers; (b) Zone with reduced vegetation cover; (c) General view of the northern sector in 2022

To ensure hydrological and hydraulic safety, targeted low-disturbance interventions were implemented, including localised channels and internal connections to restore surface drainage continuity towards the new overflow discharge structures. Localised fills were applied within significant depressions to re-establish the required hydraulic connectivity.

To address the factors potentially affecting vegetation performance, the closure strategy prioritised targeted drainage improvements and localised topographic adjustments aimed at eliminating persistent ponding and restoring hydraulic connectivity across the impoundment. Consistent with the low-disturbance closure objectives, the design did not seek to eliminate all temporary surface water accumulation, recognising that limited and short-duration ponding may still occur following infrequent high-intensity rainfall events. As a complementary mitigation measure, the revegetation protocol was refined to evaluate techniques and native species with greater tolerance to occasional and transient waterlogged conditions, while remaining consistent with the target Amazonian ecosystem and the objective of minimising disturbance to the established landform.

4 Closure concept and design basis

To achieve decharacterisation of the facility in accordance with Brazilian regulatory requirements (ANM 2022), the SP-2/3 closure concept was developed as an integrated engineering and environmental strategy.

The implementation carried out in 2023 and the design basis considered applicable Brazilian technical standards (e.g. NBR 13028:2017) and international best practices, including the GISTM (GISTM 2020).

A core premise of the closure concept was to enable compliant decharacterisation outcomes while maintaining a low-disturbance approach, prioritising preservation of established vegetation, minimisation of tailings remobilisation, and restoration of effective surface drainage pathways to eliminate persistent ponding and reduce residual hydrological and environmental risks.

4.1 Closure measures and low-disturbance interventions

The closure concept comprised a set of targeted measures designed to reinstate surface hydraulic connectivity and provide robust overflow capacity under extreme rainfall conditions, while limiting internal earthworks. Figure 8 highlights the main interventions, which are detailed in the bullet points below.

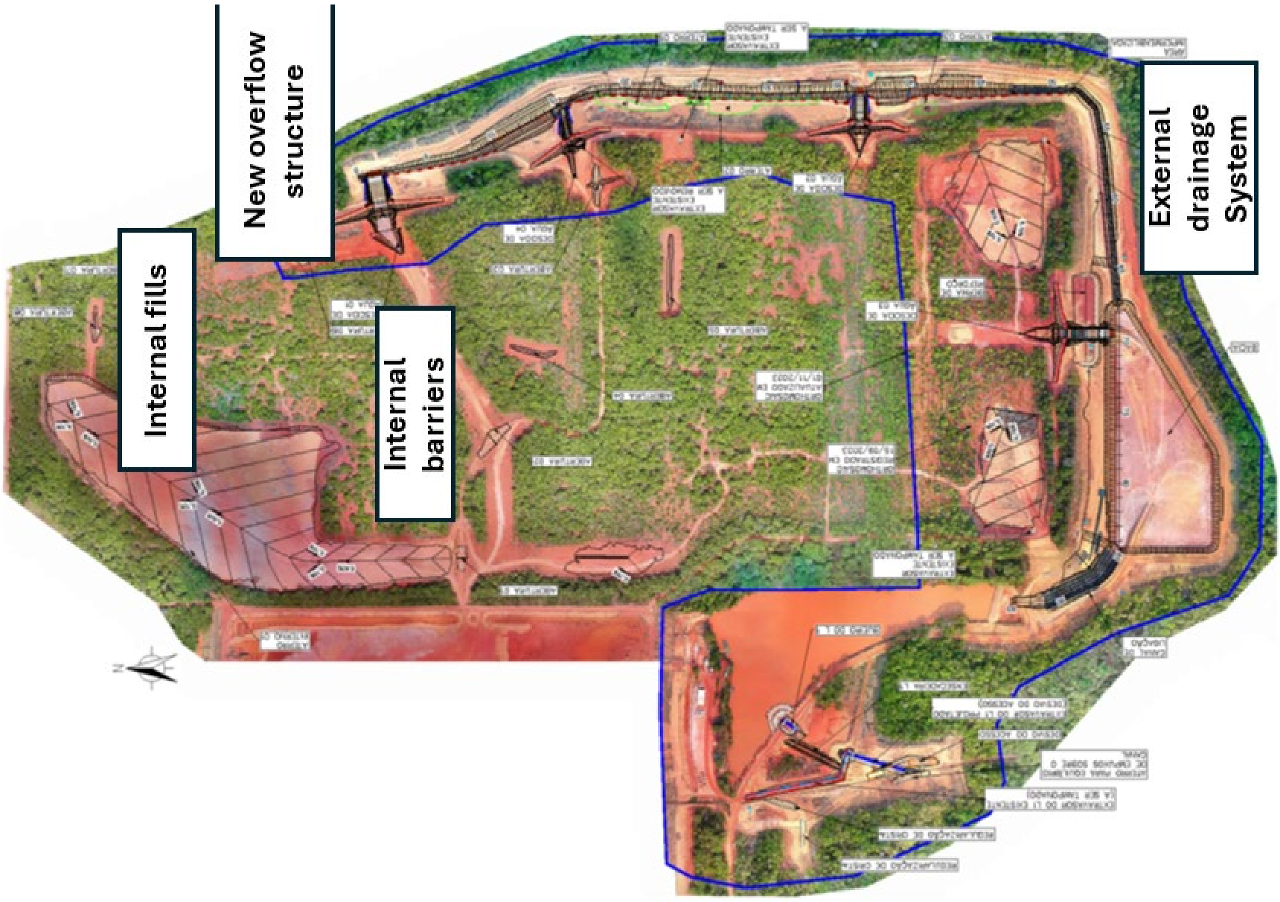


Figure 8 Main interventions

The design basis did not seek to eliminate all temporary surface water accumulation across the facility. Instead, the objective was to eliminate persistent ponding capable of adversely affecting revegetation performance or disrupting surface hydraulic connectivity. Targeted earthworks, drainage connections and overflow structures were implemented to eliminate persistent ponding under recurrent rainfall conditions, while maintaining a low-disturbance closure approach. Limited- and short-duration ponding associated with infrequent extreme rainfall events was considered acceptable, provided that the drainage network and overflow structures maintain safe conveyance capacity. The overflow system was designed to safely accommodate probable maximum precipitation (PMP)-level inflows, and closure performance was verified through field inspections and water level monitoring in previously ponded areas. The adopted design basis was supported by hydrodynamic simulations were performed using Hydrologic Engineering Center – River Analysis System (HEC-RAS), calibrated against monitored rainfall events and observed inundation patterns, including intense rainfall events that generated temporary inundation within the reservoir.

The main interventions are:

- Localised openings through major internal barriers
    - Localised openings were created across major internal topographic barriers to allow water transfer between previously disconnected internal compartments and to route run-off toward designated overflow discharge points.
- Localised internal fills to remove critical depressions and define drainage gradients
    - Internal fills were placed in areas characterised by significant depressions and recurrent water accumulation to re-establish hydraulic continuity and to support stable flow routing within the impoundment. Where implemented, fill geometries were developed to achieve gentle surface gradients (typically 0.5–0.7%) compatible with low-energy drainage conveyance and minimal disturbance objectives.
- New overflow structures to ensure hydrological and hydraulic safety
    - Four new overflow structures were implemented to connect the internal drainage system to external drainage pathways and to ensure hydrological and hydraulic safety against overtopping during extreme rainfall events. The system was designed to provide overflow capacity consistent with conservative event selection, including consideration of PMP and was framed to meet GISTM (GISTM 2020) expectations for robust performance irrespective of the facility's consequence classification.
- Long-term physical stability measures and erosion control
    - Complementary measures were adopted to support long-term physical stability under extreme environmental conditions, including reinforcement features (e.g. berms) and erosion control actions.
- Updated revegetation protocol
    - Revegetation was implemented under an updated environmental protocol, including treatments intended to improve vegetation establishment in areas subject to intermittent shallow water presence, consistent with the low-disturbance intent and the diagnostic findings.
- Monitoring strategy
    - A monitoring program was defined to assess the effectiveness of the implemented measures for a minimum period of 5 years, reflecting the time frame required to verify revegetation performance and overall closure outcomes.

4.2 Construction strategy and optimisation of internal works

During the study phase, multiple intervention scenarios were assessed to evaluate their influence on internal water retention and to optimise the extent of internal earthworks. Using the detailed topographic model, areas of persistent water accumulation – generally coincided with zones of limited vegetation development – were delineated, and internal connections were designed to enable controlled conveyance of run-off from these areas towards designated discharge points.

Surface water behaviour following rainfall events was explicitly evaluated to identify the most appropriate locations for overflow structures and, where necessary, localised crest openings to convey run-off from internally ponded areas to the exterior of the impoundment. This assessment directly informed the final positioning of the overflow systems, as well as the definition of internal openings and the placement of localised fills required to restore hydraulic connectivity between depressions and the external drainage pathways, while maintaining a low-disturbance approach.

Fills were adopted as a key measure to reduce water retention and to improve drainage effectiveness, while also supporting constructability constraints along the internal flow paths. Fills were used to limit excavation depths along the connecting channel alignment (typically avoiding depths greater than ~2.5 m), thereby reducing tailings disturbance and improving the overall mass balance of the works when considered together with excavation requirements external to the facility.

Field implementation confirmed that the as-built condition was consistent with the design intent and closure objectives.

5 Results

Post-closure monitoring was implemented to assess the effectiveness of the adopted closure measures and to verify compliance with the project objectives. The monitoring strategy focused on 3 complementary domains: environmental water quality, performance of surface drainage and overflow structures, and geotechnical behaviour.

5.1 Surface water management and water quality performance

Surface water generated within the SP-2/3 footprint is currently directed to MRN's internal water management system. Water quality monitoring focuses on run-off that comes into contact with the tailings surface and is discharged through the newly implemented overflow structures. Monitoring points were established at the 4 overflow structures (EXT-1, EXT-2, EXT-3 and EXT-4).

Water quality analyses were conducted for turbidity (NTU) and settleable solids (mL/L), and results were evaluated in relation to rainfall events. As shown in Figure 9, turbidity values exhibited temporal variability across the monitoring points, with increases generally associated with precipitation events, reflecting sediment mobilisation driven by surface run-off during rainfall.

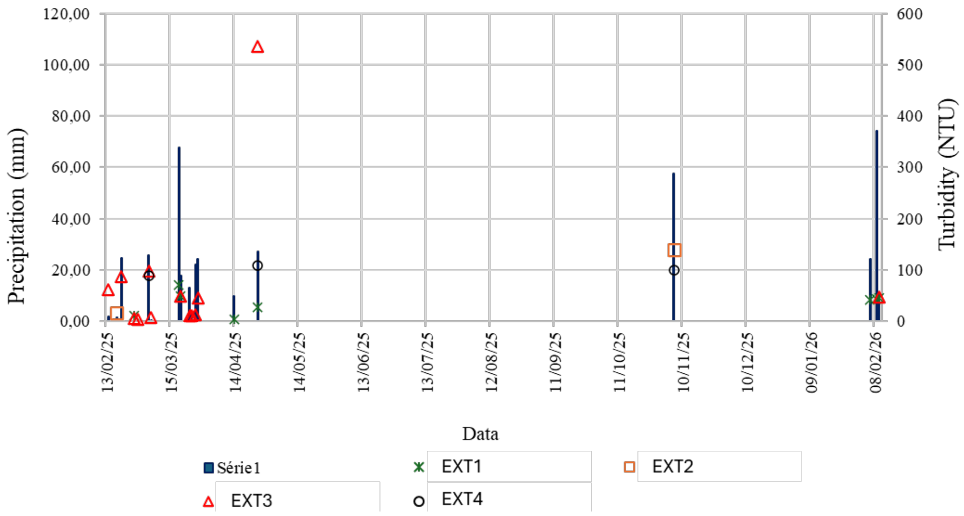


Figure 9 Turbidity measurements and precipitation

As shown in Figure 9, EXT-1 and EXT-2 exhibited moderate turbidity values, typically below 150 NTU, while EXT-4 showed an intermediate behaviour with occasional increases during rainfall events. EXT-3 recorded a single isolated event of elevated turbidity. These responses are consistent with the early post-construction phase, when some areas remained under progressive vegetation establishment and surface stabilisation.

Although run-off from the facility currently remains within MRN's internal water management system and is not directly discharged to the receiving environment, Conselho Nacional do Meio Ambiente (CONAMA) Resolution No. 357/2005 (CONAMA 2005) values were used solely as reference benchmarks to contextualise the monitoring results. They were not adopted as closure performance criteria, but only as a recognised reference framework for interpreting the observed water quality data.

According to CONAMA Resolution No. 357/2005 (CONAMA 2005), freshwater bodies are classified based on their intended uses, with more restrictive turbidity limits applied to Class I waters (≤40 NTU), which require higher environmental protection and simplified water treatment. For Class II and III waters, turbidity limits of up to 100 NTU and true colour values up to 75 mg Pt/L are permitted, reflecting the acceptance of conventional or advanced treatment processes. These values are presented herein solely as a reference, since the monitored water remains within MRN's internal water management circuit and is not discharged into receiving water bodies.

5.2 Settleable solids and depositional risk

Settleable solids were assessed using a 1-hour Imhoff cone test, as required by CONAMA Resolution No. 430/2011 (CONAMA 2011), which establishes a maximum allowable limit of 1.0 mL/L for effluent discharge into surface water bodies. Furthermore, for receiving environments with negligible circulation velocity, such as lakes and lagoons, settleable materials are required to be virtually absent due to their cumulative depositional impact.

Monitoring results presented in Figure 10 show that settleable solids were predominantly below 0.2 mL/L across all discharge points throughout the monitored period. These values represent performance significantly better than the regulatory limit and are consistent with the technical interpretation of 'virtual absence' of settleable solids for low-energy receiving environments.

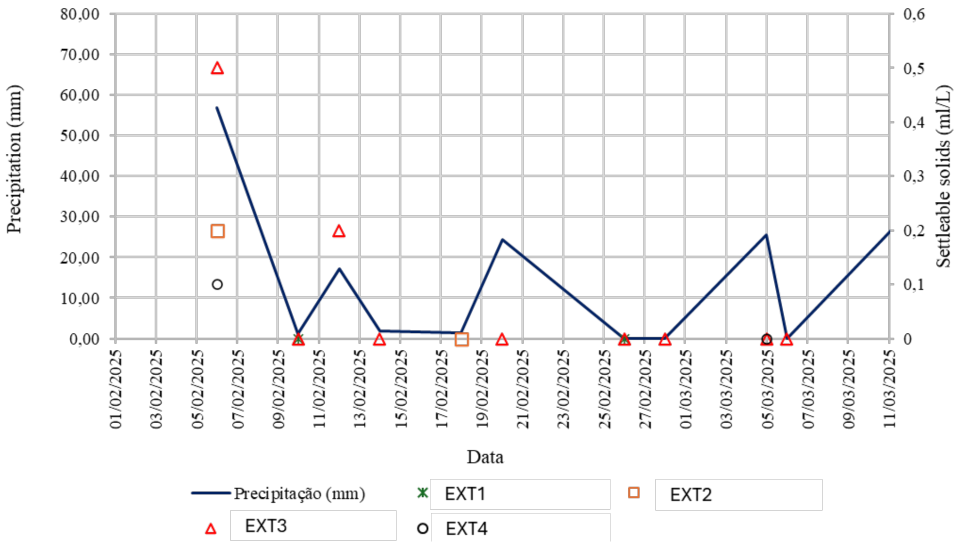


Figure 10 Variation of settleable solids (mL/L) over the monitoring period, correlated with precipitation events

5.3 Performance of drainage and overflow structures

Routine field inspections of the drainage system and overflow structures confirmed satisfactory hydraulic performance throughout the monitoring period. The overflow structures operated as intended during rainfall events, providing controlled conveyance of surface run-off and preventing the formation of persistent ponding within the former impoundment.

As shown in Figure 11, the visual inspections also confirmed good structural condition and effective integration between internal drainage pathways, overflow structures and downstream drainage infrastructure. These observations demonstrate that the closure system is functioning reliably under current climatic conditions.

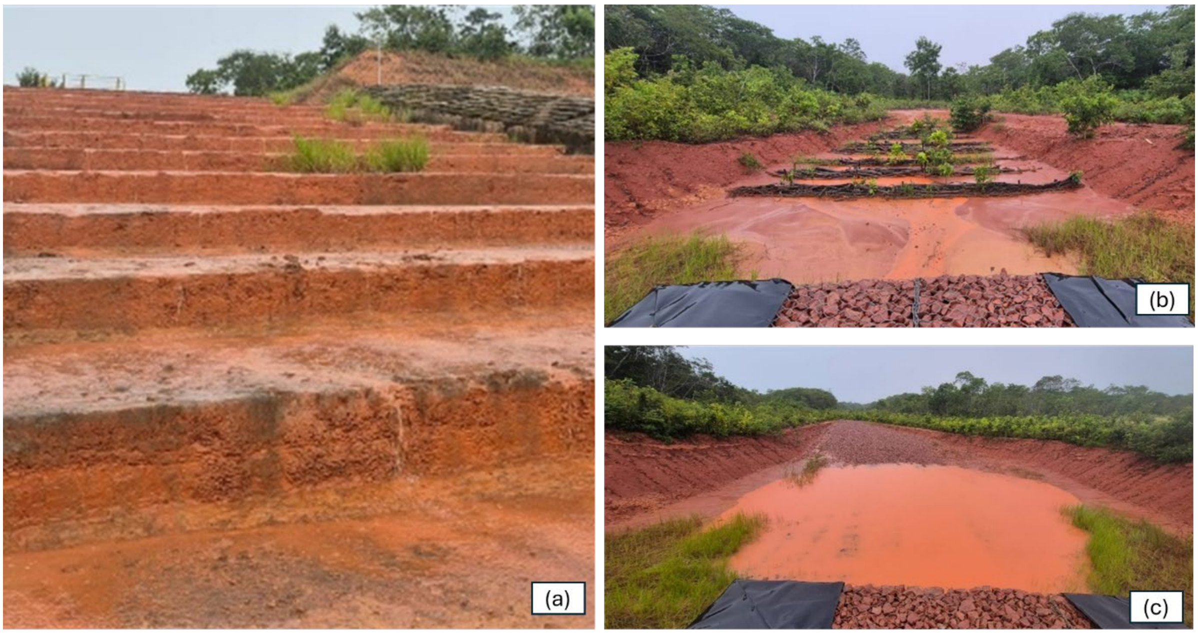


Figure 11 (a) Performance of the stepped spillway; (b) and (c) Concentration of upstream drainage toward the overflow structure and sediment retention barriers

5.4 Geotechnical monitoring performance

Geotechnical monitoring focused on percolation behaviour and long-term stability, using a network of 26 electric piezometers distributed across 5 instrumented sections. Instruments located in sections with a downstream lake exhibited piezometric variations consistent with fluctuations in lake water level. In the remaining sections, reading indicated the absence of sustained internal flow conditions.

These results support the interpretation that the tailings mass is not subject to active seepage regimes and that long-term surface stability is being maintained, consistent with the diagnostic findings and closure design assumptions.

5.5 Revegetation outcomes

Revegetation activities started immediately following completion of the closure works in December 2023. During the wet season of the first half of 2024, revegetation works included the planting of 19,914 individuals representing 18 native tree species from 6 botanical families.

Figures 12–14 presented the visual assessments and comparative imagery demonstrate preservation of most pre-existing vegetation on the tailings surface, alongside gradual and sustained development of newly planted vegetation. A general overview of the facility indicates widespread vegetation cover, while treated areas previously affected by water accumulation show marked improvement in vegetation establishment and growth following topographic adjustments and drainage improvements.

Figure 12 Aerial view of the area following intervention (2024) and during post-closure monitoring in 2025 and 2026

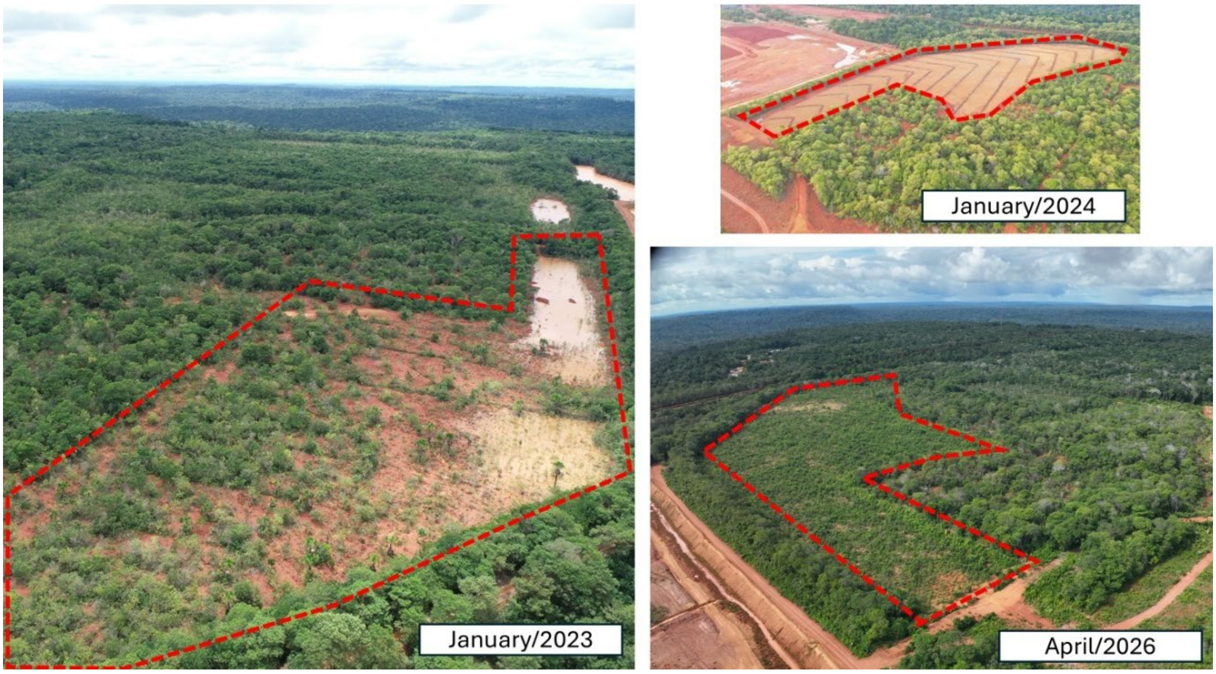


Figure 13 Treatment of the northern sector

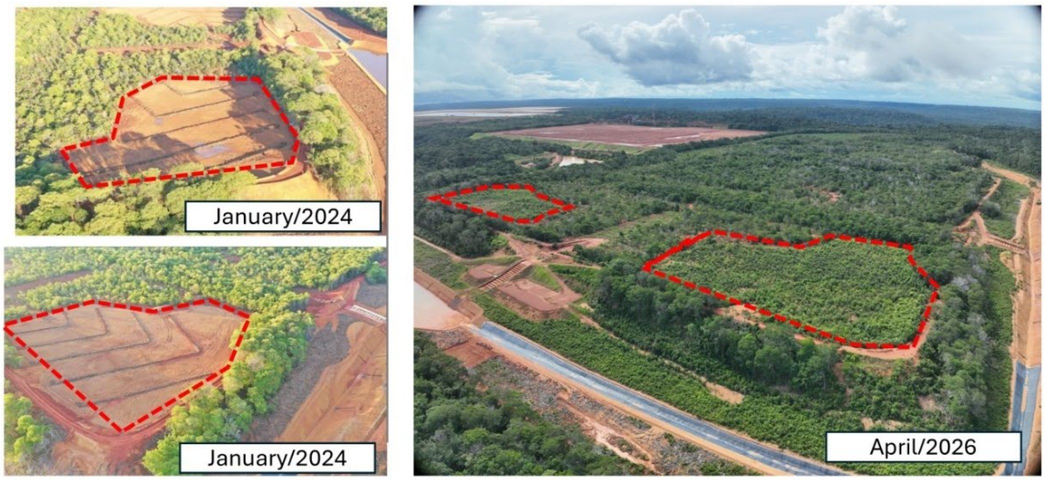


Figure 14 Treatment of the southeast sector

Based on the results obtained to date, the adopted engineering interventions have supported ecological recovery rather than replacing it, reinforcing the effectiveness of an integrated, low-disturbance closure approach in a sensitive tropical environment. Ongoing post-closure monitoring and complementary environmental actions, including invasive species removal, continue to be implemented to confirm long-term system performance and support sustained ecosystem stability and vegetation development.

6 Conclusion

The SP-2/3 bauxite tailings facility represents a legacy structure developed prior to the introduction of actual decharacterisation requirements in Brazil and current international expectations for tailings management. Following approximately 2 decades of natural recovery, the facility presented the opportunity – and the challenge – of achieving regulatory-compliant closure while preserving established vegetation and minimising disturbance to the tailings surface.

This paper demonstrated that a diagnostic-led, low-disturbance closure approach, grounded in integrated geotechnical, hydraulic and environmental assessments, can successfully address residual risks in environmentally sensitive settings. Detailed evaluation of tailings consolidation, surface morphology and drainage behaviour provided the technical basis for targeted interventions focused on restoring surface drainage connectivity, managing localised water accumulation and supporting long-term revegetation, rather than relying on extensive remobilisation of tailings.

Post-closure monitoring to date – covering a recent initial period – has confirmed the effectiveness of the adopted measures. The drainage and overflow systems performed as intended during rainfall events and geotechnical monitoring supported the long-term surface stability assumptions. Revegetation outcomes further indicate that engineering interventions enabled ecological recovery to progress, rather than replacing natural processes, with widespread preservation of pre-existing vegetation and sustained development of newly planted species. Continued monitoring and adaptive environmental management actions remain ongoing to verify long-term performance and support sustained ecological development.

The SP-2/3 case study highlights the value of a diagnostic-based evaluation of terrain morphology, surface water behaviour and environmental conditions to guide low-disturbance decharacterisation strategies. This integrated approach enabled the definition of effective closure solutions with minimal internal intervention, supporting safe and sustainable outcomes under modern regulatory requirements.

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