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Diagnosis and definition of closure success criteria for a waste rock dump: a practical case study

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Abstract

The closure of waste rock dumps is part of the mining life cycle, requiring a multidisciplinary approach to ensure long-term physical stability, environmental quality, and regulatory compliance. This paper aims to present the assessments, criteria and assumptions adopted for the closure design of an iron ore waste rock dump named PDE Sul (the Portuguese acronym) located at the Córrego do Feijão mine in Brumadinho, Brazil. Inactive since 2001, the structure was selected as a pilot asset for the application of closure practices grounded in local standard NBR 13.029:2024 (Associação Brasileira de Normas Técnicas [ABNT] 2024a) and complemented by international references such as International Council on Mining and Metals (ICMM 2025).

A comprehensive site investigation program was conducted including drillings, geotechnical sampling and testing, hydraulic verification, and ecological surveys. These diagnostics informed the development of success criteria across five key aspects: geotechnical stability, chemical stability, biological stability (erosion control and ecological restoration), interdisciplinary integration and long-term care and risk limitation. Specific indicators such as safety factor thresholds, water quality parameters, vegetation cover targets, and monitoring protocols were defined to guide implementation and long-term evaluation.

The closure design incorporates conservative slope stability analysis, surface water management systems verification, revegetation with native species, and a phased monitoring strategy. The results demonstrate how legacy structures can be transitioned into stable and environmentally integrated landscapes through performance-based planning and adaptive management. The framework presented here offers a replicable model for mining companies and regulators seeking to improve closure outcomes for similar waste rock facilities.

Keywords: *mine closure, waste rock dumps, success criteria, geotechnical stability, environmental rehabilitation, post-closure monitoring*

1 Introduction

Closing mining structures such as waste rock dumps involves complex geotechnical, environmental, social, and economic considerations. As expectations around mine closure evolve, stakeholders increasingly demand strategies that restore environmental functions, reduce long-term risks, and support future land use. Regulatory frameworks from the Brazilian National Mining Agency (ANM) and international guidance, including the International Council on Mining and Metals (ICMM), emphasise the importance of integrating closure planning from the early stages of mine development.

The PDE Sul waste rock dump, located in Brazil's iron quadrangle and inactive since 2001, was selected as a pilot site to apply and evaluate best practices in mine closure. Figure 1 illustrates its location and general layout. The site presents legacy challenges typical of older structures, including limited internal drainage and historical stability concerns, making it a relevant case for testing integrated closure methodologies.

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Figure 1 View of PDE Sul and its location within the Córrego do Feijão mine

This study presents a performance-based closure approach, grounded in applicable national technical standards that define minimum requirements for geotechnical stability, drainage, and environmental protection. The project also incorporates international best practices, including technical recommendations from Hawley & Cunning (2017), and follows established methodologies for geochemical characterisation and waste classification to determine environmental hazard potential, as outlined in relevant Brazilian regulatory frameworks.

The paper is structured as follows. Section 2 describes the site and summarises the technical investigations conducted. Section 3 outlines the closure design methodology. Section 4 presents the success criteria established to evaluate closure performance. Section 5 details the objectives that guided the conceptual design. Section 6 discusses the implementation measures required to achieve the defined success criteria. Section 7 offers recommendations for post-closure management. Finally, Section 8 concludes the study by reflecting on its broader implications and replicability.

2 Site description and background

The PDE Sul waste rock dump is located within the Córrego do Feijão mine in the municipality of Brumadinho, Minas Gerais, Brazil. It is part of the legacy mines complex, a region characterised by intense mining activity and complex geological formations. The structure was constructed using an uphill stacking method to accommodate overburden from the mining of itabirite and phyllite. Over its operational period in 2001, the dump reached 75 m height and a total volume of 3.6 Mm^3. Its geometry includes 10 m lifts, berms of similar width, and an overall slope inclination of 21˚ (1V:1.7H). The top plateau is currently used for temporary storage of filtered tailings, although this use is transitional and not part of the long-term closure vision. Figure 2 presents the current scenario of the PDE Sul.

Figure 2 PDE Sul current scenario

Since 2001, multiple technical evaluations were carried out. Early assessments identified deficiencies in internal drainage and localised stability concerns. Reports by Geoestável (2018) and WSP (2025) confirmed the absence of internal drains, although a riprap toe drain was executed to manage basal runoff. This condition has required active maintenance regarding erosion control and surface water management. Instrumentation installed includes one piezometer, one water level indicator, and a flow meter at the toe drain outlet, which are monitored periodically.

Subsurface investigations revealed that the dump is founded on weathered gneiss of the Bonfim complex, overlain by colluvial and saprolitic materials. These materials were characterised through a combination of borehole drilling, standard penetration tests (SPT), infiltration testing, and laboratory analyses. The results indicated permeability values ranging from 10^{-2} cm/s in the dump material to 10^{-5} cm/s in the underlying foundation soils. These values are critical for assessing percolation potential, physical stability, and the design of surface water devices.

Hydrological modelling conducted by MDGEO (2024) further informed the closure strategy. The analysis confirmed that groundwater flow from the adjacent Cava Feijão pit does not interact with the PDE Sul system. This hydrological independence simplifies the closure design by reducing the need for complex groundwater control measures and reinforces the feasibility of implementing a low-maintenance closure solution.

Initial geotechnical analyses conducted in the mid-2000s revealed local factors of safety below the thresholds established by Associação Brasileira de Normas Técnicas (ABNT 2024a) NBR 13.029 . Although reinforcement measures were recommended at the time, they were not implemented. Subsequent evaluations, including those by Geoestável (2018), incorporated updated topographic and instrumentation data. These later studies confirmed that the structure meets global stability requirements, with Factors of Safety equal to or greater than 1.5 under static conditions and 1.3 under critical scenarios. It is important to note that the critical scenario is associated with a condition of elevated phreatic surface within the waste rock mass, which increases porewater pressures and reduces effective stress, thereby influencing slope stability. These findings provided the technical basis for advancing to the conceptual closure phase.

Regarding the post-closure land use, according to Vale's internal land use classification system, the PDE Sul structure is located within a 'zone of re-signification'. This designation reflects its potential for environmental and social reintegration, particularly through passive land uses such as conservation, education, or ecological restoration.

In summary, the PDE Sul waste rock dump presents a technically stable but environmentally sensitive structure. Its legacy conditions, combined with the absence of internal drainage and the presence of saprolitic foundations, require a closure strategy that balances geotechnical conservatism with ecological functionality. The site's classification as a re-signification zone underscores its potential to serve as a model for the closure of similar legacy structures in Brazil and beyond.

3 Closure design methodology

The design of mine closure strategies plays a central role in ensuring the long-term safety and sustainability of post-mining landscapes. For waste rock dumps, closure must address persistent risks such as slope instability, erosion, geochemical contamination, and ecological degradation. International guidance, including the ICMM (2025) *Integrated Mine Closure Good Practice Guide*, emphasises that closure planning should begin early in the mine life cycle and integrate technical, environmental, and social dimensions. In Brazil, the ABNT NBR 13.029:2024 standard establishes minimum requirements for the design, operation, and closure of waste rock piles including criteria for structural stability, environmental protection, and land use compatibility. However, while the standard does address these topics, its guidance on closure and post-mining land use remains relatively generic and lacks the level of specificity needed to support detailed, site-specific planning and implementation.

> *"This standard establishes the requirements for the development and presentation of waste rock pile projects generated by open-pit or underground mining operations, aiming to meet conditions of safety, operational efficiency, cost-effectiveness, and closure, while minimizing environmental impacts." ABNT NBR 13.029 (ABNT 2024a)*

The conceptual project, prepared by WSP (2025), aligns with both national regulations and international best practices, including those outlined by Hawley & Cunning (2017). The design integrates multidisciplinary data to manage residual risks and enhance the structure's resilience to future changes in climate and land use. This approach reflects a shift from reactive closure to proactive landscape planning, where closure is not only a technical requirement but also a tool for environmental recovery.

The closure strategy for PDE Sul is structured around five core dimensions: geotechnical stability, chemical stability, biological stability (erosion control and ecological restoration), interdisciplinary integration and long-term care and risk limitation. Each of these components was analysed in detail and technically justified based on site-specific data. The design aims to ensure that the structure remains physically stable, chemically inert, and ecologically functional over the long-term.

Geotechnical stability was addressed through slope stability modelling using limit equilibrium methods, incorporating conservative strength parameters derived from laboratory testing and back-analysis. Hydraulic performance was evaluated through runoff modelling and verification of the surface drainage in place and geochemical assessment was supported by testing gross mass, metal leaching and solubilisation potential for waste rock classification, in accordance with the procedures defined in ABNT NBR 10004:2024 (ABNT 2024b), which establishes criteria for classifying solid waste based on its hazardous potential to human health and the environment. Ecological restoration was guided by vegetation surveys and land use zoning, with targets for native species cover and biodiversity indicators.

This methodology provides a foundation for the implementation of a closure plan that is technically robust, environmentally sound, and socially acceptable. It also establishes a replicable model for the closure of other legacy waste rock dumps in Brazil and similar mining regions.

3.1 Geotechnical stability

Ensuring the physical stability of the waste rock dump is a fundamental requirement of the closure strategy for PDE Sul. No other form of long-term stability (i.e. chemical, ecological, or social) can be achieved unless the structure remains safe and stable.

The conceptual design developed by WSP (2025) applied limit equilibrium methods, specifically the Spencer and Morgenstern-Price techniques, to evaluate slope stability under both static and critical conditions. The critical condition considered in the analysis corresponds to an elevated phreatic surface within the waste rock mass, which increases porewater pressures and reduces effective stress, thereby representing a conservative scenario for slope stability assessment, this approach aligns with the hydrogeological considerations discussed by Beale & Read (2013), particularly regarding the influence of groundwater on slope stability. Moreover, the principles from Read & Stacey (2009) guided the broader understanding of slope failure mechanisms in open pit contexts. These methods considered circular and composite failure surfaces, which are appropriate for the heterogeneous nature of the dump materials and the underlying saprolitic foundation.

Strength parameters used in the analyses were derived from laboratory testing and back-calculation based on historical performance data. Conservative values were adopted to account for material variability and uncertainties in subsurface conditions. The results demonstrated that the structure meets widely accepted safety thresholds, with global factors of safety equal to or greater than 1.5 under static conditions and 1.3 under critical scenarios. Although the 2024 edition of ABNT NBR 13.029 no longer explicitly defines a critical phreatic condition or prescribes a minimum Factor of Safety for pseudo-static analyses, these criteria were adopted in the project as good engineering practice to ensure a conservative and robust stability assessment.

Considering the current slope inclination of approximately 21 degrees (1V:1.7H), the assessment of berms and benches to evaluate their functionality in controlling surface runoff and minimising erosion and the results of the stability analysis, slope reconfiguration was not required. However, the analysis considered national technical recommendations for berm width in waste rock piles as presented by Pinheiro (2011), and minor reshaping was proposed where necessary.

3.2 Chemical stability

Geochemical characterisation considered the selection of matrices for sampling based on the geochemical composition, not only of the rock substrates but also of the aqueous matrix samples, which reflect the local/regional geology and represent the load of dissolved and suspended elements resulting from anthropogenic activities.

In this context, the set of samples included materials that represent waste rock; residual soil; natural soil; surface water (including water from bottom drain) and groundwater.

Geochemical characterisation was planned to occur in a phased approach. The first phase comprises tests of gross mass, metal leaching, and solubilisation potential for waste rock classification. The results will indicate if static and kinetic tests to assess acid rock drainage (ARD) potential, including acid-base accounting (ABA) and humidity cell testing, will be necessary.

For the conceptual design, the assumption that the waste rock material will not be able to contribute contaminants to the local environment was assumed.

Furthermore, the conceptual project indicated to properly monitoring the surface water quality downstream and consider the concentrations obtained in background and baseline studies as a reference. These studies provide fundamental data on the natural conditions of environmental matrices, including water bodies. Thus, it is possible to compare monitoring results with natural quality levels and identify variations that require corrective actions.

The monitoring of effluent quality from the structure’s bottom drain was also recommended, given its importance as a criterion for maintaining chemical stability. When effluents are not treated or monitored properly, they can carry contaminants capable of compromising the receiving water bodies and negatively affect aquatic ecosystems and human communities downstream. Therefore, ensuring that effluent quality standards meet the limits established by environmental legislation is an essential step for environmentally responsible closure.

3.3 Biological stability

In the context of mine closure, biological stability plays a fundamental role in ensuring long-term environmental resilience and landscape recovery. At PDE Sul, this dimension of stability is structured around three interdependent components: erosion control, environmental reintegration, and vegetative cover. While each plays a distinct role in supporting long-term ecological recovery, environmental reintegration and vegetative cover are closely linked and often implemented in tandem.

Together, these elements form the basis for restoring ecological functions and minimizing post-closure impacts. Erosion control measures are designed to reduce runoff velocity and sediment transport, while environmental reintegration aims to harmonize the waste rock pile with the surrounding landscape. Vegetative cover, in turn, supports both erosion mitigation and biodiversity recovery, with specific targets and monitoring indicators guiding its implementation.

This integrated approach reflects the broader commitment to sustainable closure planning, aligning technical interventions with ecological processes and regional conservation goals.

3.3.1 Biological integration and vegetative cover

Biological integration is a key component of the long-term success of mine closure, particularly in regions where ecological resilience is essential for landscape recovery. At PDE Sul, the closure design includes specific revegetation goals aimed at re-establishing native species and supporting broader ecological functions.

The primary target is to achieve a minimum of 70% surface vegetative cover within five years of implementation, using species adapted to local conditions and capable of contributing to reduce soil loss runoff velocity and minimising sediment transport.

The selection of plant species was informed by floristic surveys conducted in adjacent undisturbed areas, as well as by performance data from previous rehabilitation efforts within the Córrego do Feijão area.

The analysis of the current vegetation coverage was carried out based on field survey the analysis of the vegetation coverage in the pile, considering the density and health of the vegetation, calculated by the normalised difference vegetation index (NDVI). By integrating NDVI data into the application of the universal soil loss equation, it becomes possible to identify areas with insufficient vegetation cover, which are more susceptible to erosion. This approach allows prioritising and supporting revegetation actions in strategic locations, contributing to the mitigation of environmental impacts.

Figure 3 shows the NDVI values obtained for the PDE Sul area and surroundings, according to the colorimetric gradient. Areas with a colour closer to green indicate greater coverage and better quality of vegetation, and redder areas indicate absence of vegetation or less abundant vegetation and lower quality.

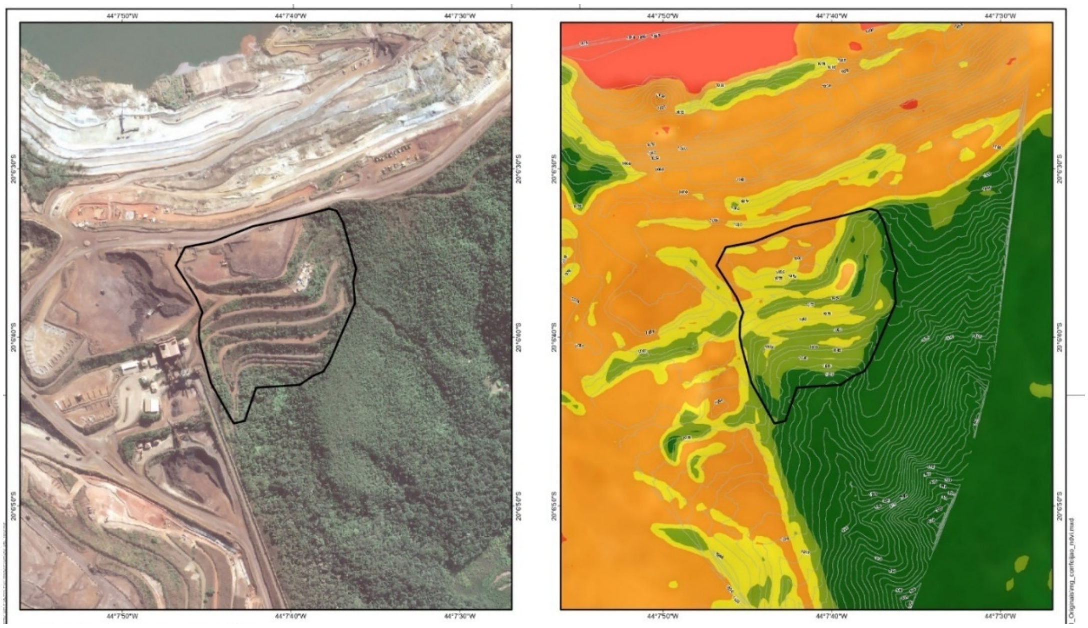

Figure 3 Normalised difference vegetation index modelling (source: WSP (2025) - RL-1190JJ-X-15131)

As described, PDE Sul includes regions with absent or very sparse vegetation cover, where initial revegetation followed by forest enrichment is recommended, as well as areas with well-established vegetation that will only require forest enrichment.

In addition to vegetative cover targets, the biological design incorporates biodiversity indicators and invasive species control measures. These parameters support the assessment of ecological recovery and help align site rehabilitation with broader regional conservation efforts.

To support early vegetative establishment, the design includes a series of soil preparation and amendment techniques. These measures involve the application of organic mulch, the incorporation of nutrient-rich topsoil or composted material, and surface treatments to improve moisture retention and seed germination.

Where necessary, hydroseeding and direct planting methods are used to accelerate vegetation development and reduce erosion risks during the initial post-closure phase.

3.3.2 Erosion control

To quantify erosion risk and guide surface stabilisation measures, the design team applied the revised universal soil loss equation (RUSLE), a widely used empirical model for estimating soil loss under varying land use and climatic conditions. Additionally, this model is based on the foundational work by Wischmeier & Smith (1978), which remains a cornerstone in empirical erosion prediction methodologies. Jones (1996) provides a broader theoretical foundation for understanding soil erosion processes and supports the application of empirical models like RUSLE in land rehabilitation contexts.

The modelling established an acceptable soil loss threshold of less than 11 t/ha per year. This benchmark is consistent with the requirements of ABNT NBR 13.029:2024 which establishes technical criteria for erosion control in waste rock piles, including acceptable soil loss thresholds and parameters for slope geometry, drainage, and vegetative cover, which support the benchmark adopted in this study, and also the recommendations of Wall et al. (2002) that provide technical guidance on acceptable soil loss thresholds in post-mining landscapes, supporting the benchmark of less than 11 t/ha per year used in this study. The analysis incorporated site-specific parameters, including slope length and gradient, rainfall erosivity, soil erodibility, and vegetation cover.

Based on the RUSLE outputs and field observations, the closure design proposed specific interventions aimed at reducing runoff velocity and minimising sediment transport. These measures included the reshaping of berms to improve flow distribution, the installation of vegetated swales to intercept and slow surface water, and the use of localised armouring in areas with concentrated flow or high erosion potential. Surface regrading was also incorporated into the design to eliminate irregularities that could lead to ponding or channel formation. The selection of these interventions was guided by both hydraulic modelling and practical considerations related to constructability and long-term maintenance. Figure 4 illustrates the hydraulic modelling developed for the current condition of the PDE Sul that supported the closure interventions related to surface drainage and erosion control.

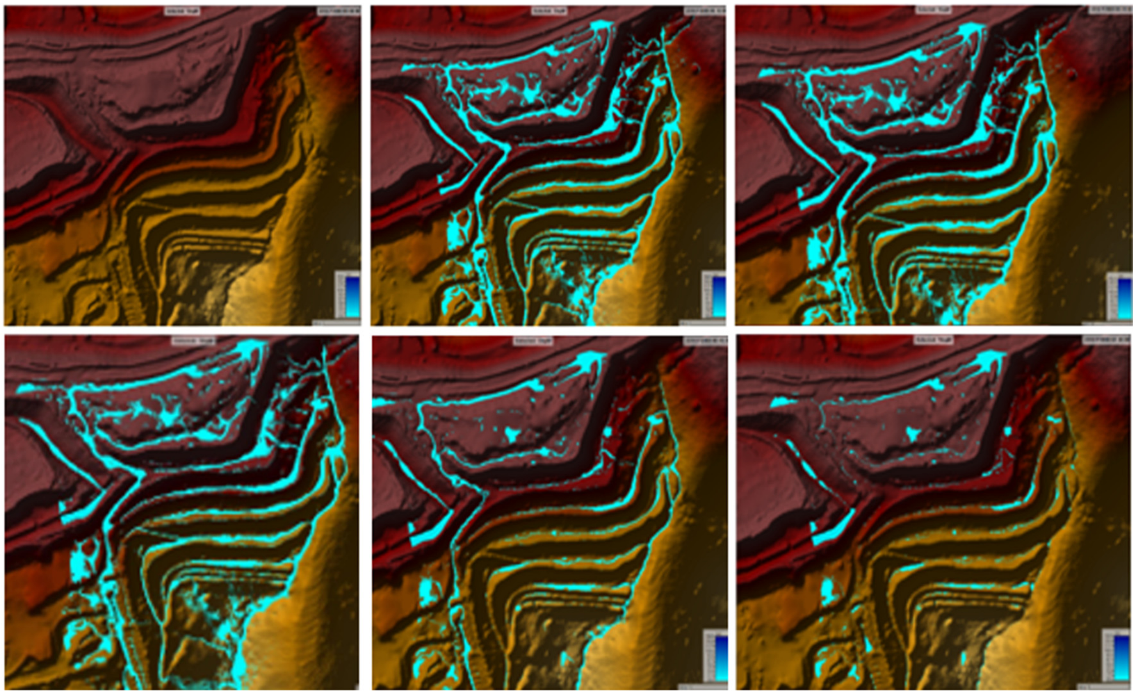

Figure 4 PDE Sul modelling (source: WSP (2025) - RL-1190JJ-X-15131)

The RUSLE model, supported by site-specific data and aligned with national and international standards, provided a solid basis for designing effective erosion control measures at PDE Sul. Combined with hydraulic modelling, the proposed interventions – such as berm reshaping, vegetated swales, and localised armouring – aimed to improve surface stability and reduce sediment transport. As illustrated in Figure 4, this integrated approach supports the long-term environmental performance of the site and highlights the value of data-driven planning in mine closure.

3.4 Interdisciplinary Integration

The closure plan for PDE Sul was developed through a coordinated, interdisciplinary approach that brought together geotechnical, environmental, hydraulic, and ecological expertise. This integration ensured that each technical domain informed and reinforced the others, enabling a comprehensive understanding of site conditions and closure needs. The strategy was implemented in phases, allowing for progressive refinement of solutions as new data became available and as the site evolved. This phased methodology supported adaptive planning, minimized long-term risks, and aligned the closure process with Vale's sustainability and regulatory commitments.

By combining multiple technical disciplines, the project team was able to address the complex interactions between physical stability, chemical behaviour, water management, and ecological recovery. This integration ensured that closure measures were not developed in isolation but were coordinated to function as a unified system.

This alignment ensured consistency across technical, environmental, and social dimensions, and reinforced the credibility of the closure strategy. The interdisciplinary coordination promoted by this approach addressed immediate geotechnical and hydrogeological challenges while also supporting the long-term transformation of PDE Sul into a stable, chemically safe, and ecologically integrated landform suitable for post-mining use.

The implementation strategy was structured around a series of technical steps, each grounded in site-specific data and designed to inform the closure design:

- Geotechnical investigations involved the execution of boreholes and SPT, along with undisturbed sampling and laboratory testing. Even though cone penetration testing with pore pressure measurement (CPTu) was not employed, complementary frameworks, such as Robertson (2005), provide valuable insight for interpreting geotechnical behaviour. These activities provided data on particle size distribution, shear strength, moisture content, and permeability, which were essential for slope stability modelling and drainage design.
- Geochemical characterisation included the collection and analysis of waste rock samples using static tests such as ABA and kinetic tests such as humidity cell experiments. These analyses evaluated the potential for ARD and the mobility of contaminants.
- Hydrological and hydraulic studies were conducted using LiDAR-based watershed delineation and field mapping. Surface runoff simulations were based on local rainfall return periods, and both existing and proposed drainage infrastructure were reviewed to ensure effective control of water flow and sediment transport.
- Environmental and landscape assessments incorporated the use of NDVI data and ecological sensitivity mapping to guide revegetation strategies. Landscape integration was guided by visual and functional criteria in line with ICMM (2025)recommendations for post-closure land use.

This structured and interdisciplinary methodology provided the technical foundation for a closure plan that is both robust and adaptable. It also ensured that the design process remained responsive to evolving site conditions and stakeholder expectations, reinforcing the long-term sustainability of the closure outcomes at PDE Sul.

3.5 Long-term care and risk limitation

Ensuring the long-term stability and safety of the PDE Sul waste rock pile requires a strategic approach to post-closure care and risk management. This criterion encompasses the minimisation of future liabilities and the reduction of maintenance needs, aiming to transition the structure into a self-sustaining condition.

The closure design integrates measures that promote passive stability, such as surface regrading, erosion control, and revegetation, which collectively reduce the likelihood of structural degradation over time. By achieving geotechnical, geochemical, and ecological stability, the site is expected to require minimal intervention beyond the initial monitoring phase.

Risk limitation is addressed through the identification and mitigation of potential environmental, social, legal, and financial risks. These include the prevention of contamination, control of invasive species, and compliance with regulatory standards. The implementation of robust monitoring programs ensures that any emerging risks are detected early and managed effectively.

Ultimately, the goal is to enable the transfer of the area to third parties without residual obligations for the operator, reflecting a successful closure process that aligns with Vale’s sustainability principles and the technical requirements outlined in ABNT NBR 13.029:2024.

4 Success criteria framework

The establishment of clear success criteria is a foundational element in effective mine closure planning. These criteria serve not only to evaluate whether closure objectives are being met but also to provide a structured framework for monitoring long-term performance. In the case of the PDE Sul waste rock dump, approached as an independent geotechnical structure, success criteria were specifically designed to address its unique risk profile, functional role, and intended post-closure land use.

As performance benchmarks, success criteria enable the systematic evaluation of closure progress across multiple disciplines and support adaptive management by facilitating early detection of deviations and timely corrective actions. Both international and national frameworks emphasise the importance of defining these criteria at the outset of closure planning. The ICMM (2025)recommends their early integration into mine planning, while Brazil’s ABNT NBR 13.029:2024 mandates the use of both quantitative and qualitative indicators to assess long-term outcomes. These typically include parameters such as slope stability, water quality, vegetation recovery, and land use compatibility.

> *“These standards mandates the use of both quantitative and qualitative indicators to evaluate the performance of waste rock pile closure, including parameters such as slope stability, water quality, vegetation recovery, and land use compatibility, ensuring long-term environmental and structural integrity.” ABNT NBR 13.029 (ABNT 2024a)*

When it comes to PDE Sul, the success criteria were established through a comprehensive site-specific assessment, incorporating geotechnical investigations, hydrogeochemical modelling, erosion risk analysis, and ecological mapping. The selection of performance indicators was guided by both technical feasibility and stakeholder engagement, ensuring that the resulting targets were realistic, context-appropriate, and measurable.

Thus, to guide this process, the project team followed the (specific, measurable, achievable, relevant, and time-bound (SMART) framework. This methodology is widely applied in mine closure planning as it supports the establishment of quantifiable performance objectives, enhances the reliability of long-term monitoring systems, and provides a structured basis for initiating corrective measures when performance deviations are detected.

The main categories and indicators used to evaluate closure success for PDE Sul are summarised in Table 1.

Table 1 Main mine closure domains and indicators

Category	Common indicators
Physical stability	Factor of Safety, absence of deformation or failure
Chemical compliance	pH, conductivity, concentrations of key metals/sulphates
Ecological recovery	Vegetative cover %, species richness, invasive species control
Legal and institutional	Compliance with licenses, audit results, documentation status

By using this framework, the PDE Sul closure strategy is aligned with both international best practices and Brazilian regulations. It also helps ensure that the structure evolves into a stable, safe, and environmentally integrated landscape. The next sections explain each of these success domains in more detail.

The formulation of clear and measurable success criteria is fundamental to ensuring that mine closure processes effectively achieve their overarching objectives: protecting the environment, ensuring geotechnical stability, supporting social reintegration, and meeting legal obligations. These criteria act as benchmarks that help track progress and guide decisions throughout the post-closure phase.

4.1 Physical stability

Ensuring long-term physical stability is a fundamental priority in mine closure planning. For the PDE Sul waste rock dump, this entails maintaining geotechnical integrity under both routine operational conditions and extreme environmental scenarios. In accordance with the Brazilian standard ABNT NBR 13.029:2024, the minimum acceptable Factor of Safety (FoS) is defined as 1.5 under drained (static) conditions. However, the standard does not establish specific FoS values for pseudo-static analyses, which are essential for evaluating performance under seismic or other critical loading conditions. In this context, the conceptual design adopted the threshold of 1.3 for pseudo-static conditions, based on the recommendations of Hawley & Cunning (2017), who suggest this value for structures classified as moderate risk.

To verify compliance with these regulatory thresholds, WSP (2025) conducted slope stability analyses using limit equilibrium methods, specifically the Spencer and Morgenstern-Price techniques. These assessments incorporated site-specific parameters, including slope geometry, subsurface stratigraphy, and material strength properties derived from laboratory testing and back-analysis. The results confirmed that the waste rock dump meets or exceeds the prescribed safety margins.

However, reliance on FoS alone is insufficient for a comprehensive evaluation of physical stability. Additional indicators include the absence of surface cracking, slippage, or deformation, as well as the effective operation of surface and subsurface drainage systems. These parameters are monitored through a combination of UAV-based topographic surveys, systematic visual inspections, and, where applicable, geotechnical instrumentation such as inclinometers.

Collectively, these indicators provide a robust understanding of the structural behaviour of the waste rock dump and support the conclusion that the facility remains stable without requiring ongoing maintenance interventions. This approach aligns with international best practices, including those outlined by Hawley & Cunning (2017), and constitutes a critical component of the integrated closure strategy developed for PDE Sul.

4.2 Hydrological performance

Managing water flow is a critical part of ensuring long-term stability and environmental safety in mine closure, especially for structures like the PDE Sul waste rock dump. At this site, both surface runoff and subsurface water behaviour directly affect slope stability and compliance with environmental standards.

According to ABNT NBR 13.029:2024 a well-designed drainage system is essential to prevent erosion, avoid water accumulation, and protect the integrity of cover systems. For PDE Sul, success in this area means that toe drains, berms, and surface channels work effectively to prevent ponding and uncontrolled runoff.

To achieve this, the closure design included LiDAR-based catchment modelling and rainfall-frequency analysis to properly size and position drainage structures. These systems were designed to handle both typical rainfall and extreme weather events, ensuring that water is safely directed to sedimentation basins or infiltration areas.

Key indicators of good hydrological performance include the absence of erosion gullies, no signs of waterlogging on the dump surface, and discharge volumes that match what was predicted in the hydrological models. Regular inspections and flow measurements are especially important in the early years after closure, when vegetation is still established and the system is most vulnerable.

This approach follows the best international practices, including those recommended by the ICMM (2025), which emphasise the need for adaptive water management. As vegetation cover improves and climate conditions evolve, the drainage system must continue to perform reliably to support both geotechnical stability and environmental goals.

4.3 Chemical stability

Chemical stability is a key indicator of whether a closed mine site can safely interact with its surrounding environment over the long-term. At PDE Sul, this means ensuring that no harmful contaminants are generated or released beyond the site boundaries.

To assess this, waste rock samples were tested using both static methods (ABA) and kinetic methods (humidity cell tests). The results showed no potential for ARD, meaning the materials are unlikely to produce acidic or metal-laden leachate over time. These findings are consistent and support a closure design that does not require engineered covers for chemical containment.

For the site to be considered chemically stable, water quality must remain within Class 1 standards for pH, electrical conductivity, and concentrations of key trace metals, as defined by CONAMA Resolution No. 420, of 2009 and site-specific baseline values. This ensures that any water leaving the site, whether through runoff or seepage, meets environmental safety standards.

> *“Establishes criteria and guiding values for soil quality regarding the presence of chemical substances and sets guidelines for the environmental management of areas contaminated by such substances as a result of anthropogenic activities.” CONAMA Resolution No. 420 (2009)*

To track this over time, the closure plan includes seasonal monitoring of both surface water and groundwater. The results are compared against regulatory thresholds and modelled expectations. Long-term chemical stability is demonstrated by consistent, predictable water quality and the absence of trends that would require active treatment systems.

This approach allows PDE Sul to meet environmental compliance goals while minimising the need for ongoing intervention, reinforcing the site’s potential for safe and sustainable post-mining use.

4.4 Biological and ecological integration

Restoring ecological function is a key part of mine closure and at PDE Sul, this means re-establishing vegetation and creating conditions that support long-term habitat recovery. The goal is to reach at least 70% vegetative cover using native species within five years, based on comparisons with nearby reference areas. This target supports not only erosion control but also biodiversity and visual integration with the surrounding landscape, in line with ICMM (2025) guidance on sustainable post-mining land use.

To track progress, the closure plan includes regular monitoring using tools such as NDVI analysis, floristic surveys, and soil stability assessments. These methods help evaluate how well vegetation is established and whether the site is moving toward a self-sustaining ecological state.

In addition to measuring plant cover, the plan also includes indicators for biodiversity, such as species richness and the presence of invasive or exotic species. The creation of microhabitats is another important element, helping to support local fauna and improve ecological resilience.

Together, these efforts ensure that the site is not just revegetated but meaningfully reintegrated into the local ecosystem. This approach aligns with Vale's broader environmental goals and supports the long-term land use vision for PDE Sul as a stable, low-maintenance, and ecologically functional landscape.

4.5 Monitoring and adaptive management

Long-term success in mine closure depends not just on good design, but on how well the site performs over time. That's why monitoring and adaptive management are essential, especially for geotechnical structures like the PDE Sul waste rock dump. These processes help track whether the closure goals are being met, identify trends, and guide corrective actions if things start to deviate from expectations.

The Brazilian standard ABNT NBR 13.029:2024 highlights the importance of continuous performance monitoring, while the ICMM (2025) recommends adaptive systems capable of responding to evolving site conditions, such as changes in climate, vegetation growth, or water dynamics. Although ANM Resolution No. 95/2022 (National Mining Agency 2022) is primarily focused on tailings dams, its principles, such as the definition of closure success criteria, long-term performance verification, and structured governance protocols, can be meaningfully extended to waste rock dumps, particularly those with significant environmental and geotechnical relevance. By establishing technical and institutional requirements for closure and post-closure management, the resolution reinforces the need for auditable and risk-informed strategies across different types of mining structures, contributing to long-term safety and environmental accountability. These guidelines reinforce the need for structured and auditable closure strategies across different types of mining structures.

At PDE Sul, a tailored monitoring programme was put in place to track key indicators across several domains. This includes long-term instrumentation and field assessments focused on:

- Slope stability: visual inspections, topographic surveys, and inclinometer readings (if installed) are used to detect any movement or deformation.
- Hydrological performance: flow meters and sediment monitoring help assess how well the drainage systems are functioning, especially during and after heavy rainfall.
- Chemical parameters: water samples are collected seasonally and tested for pH, electrical conductivity, iron, manganese, and sulphate levels, following CONAMA Resolution 420/2009.
- Vegetation: NDVI analysis and floristic surveys are used to measure vegetative cover and compare it to recovery targets.

These indicators are reviewed regularly, typically once a year, through structured analysis and field validation. If any results fall outside the expected range, pre-defined mitigation measures are triggered. This ensures that issues are addressed early, before they become long-term problems.

To support transparency and accountability, all monitoring data is documented through dashboards, audit trails, and internal reporting systems aligned with Vale's governance framework.

This feedback loop turns monitoring into more than just a reporting exercise. It becomes a dynamic management tool that helps keep the closure plan on track, even as site conditions evolve. In doing so, PDE Sul moves steadily toward becoming a stable, compliant, and socially accepted post-mining landscape, fully aligned with the principles set out by Hawley & Cunning (2017).

4.6 Institutional and governance compliance

Institutional compliance plays a key role in ensuring that mine closure is not only technically sound but also legally and socially accountable. For PDE Sul, this means demonstrating that all closure actions follow applicable laws, meet regulatory requirements, and align with Vale's internal governance standards.

To verify this, documentation must show compliance with closure licenses, adherence to the ABNT NBR 13.029:2024 standard, and conformity with Vale's internal procedures. The closure is consistent with the principles of the National Environmental Policy (Brazil 1981), which prioritises environmental integrity and restoration. This process was also guided by the Brazilian Mining Code (Brazil 1967), which defines operator responsibilities for post-operational environmental remediation. In addition, the closure planning aligns with ABNT NBR ISO 14001:2015, which provides requirements and guidance for implementing an environmental management system that supports sustainability throughout the site life cycle. Tools such as audits, performance reports, and compliance checklists are used to track and confirm that all obligations are being met.

Vale's closure framework also includes regular third-party evaluations and internal reviews. These assessments are aligned with recognised best practices in corporate governance and help ensure transparency throughout the closure process. This level of oversight not only builds regulatory credibility but also supports a smooth transition when the site is eventually handed over to land management authorities or other stakeholders.

By embedding institutional compliance into the closure strategy, PDE Sul reinforces its commitment to responsible mining and long-term accountability.

4.7 Social and land use compatibility

Social acceptance and future land use are key elements of a successful mine closure. At PDE Sul, the closure strategy was designed not only to stabilise the structure but also to ensure that the site could be reintegrated into the surrounding landscape in a way that benefits the community. The area has been designated as a 'zone of re-signification', meaning it is intended for passive uses such as conservation, education, or other low-impact activities that restore its environmental and social value.

To evaluate success in this area, several indicators are used. These include records of community engagement and consultation, the absence of post-closure complaints, visual integration of the site into the landscape, and evidence of potential for public or institutional use. These indicators help confirm that the site is not only physically and environmentally safe but also accepted and valued by local stakeholders.

This approach reflects the ICMM (2025) principle that mine closure should leave a positive socio-environmental legacy. At PDE Sul, the goal is to minimise long-term liabilities while enhancing the site's contribution to the region.

4.8 Integrated success criteria overall

Together, the success criteria across all domains – geotechnical, hydrological, chemical, ecological, institutional, and social – form a comprehensive framework for evaluating closure performance at PDE Sul. These criteria were developed to be both site-specific and scalable, ensuring they reflect the unique characteristics of the structure while aligning with broader regulatory and industry standards.

The framework is fully aligned with the Brazilian standard ABNT NBR 13.029:2024 and international best practices, including those from the ICMM (2025)and Hawley & Cunning (2017). It provides a clear roadmap for implementation, monitoring, and long-term verification.

By addressing all critical dimensions, from slope stability and water management to ecological recovery and community acceptance, the PDE Sul closure strategy offers a replicable model for progressive mine closure. The strategy reflects the objectives outlined in Brazil's National Solid Waste Policy (Brazil 2010), which promotes rehabilitation and environmentally appropriate final disposal. It lays the foundation for long-term sustainability, regulatory compliance, and reduced residual liabilities, while contributing positively to the surrounding environment and society.

5 Objectives and conceptual design

Defining closure objectives is a key step toward establishing a post-mining transition that is technically sound, environmentally robust, and socially aligned. These objectives guide the planning, implementation, and monitoring phases, helping to align site conditions with long-term post-closure goals.

In the case of the PDE Sul waste rock dump, closure objectives were developed through a comprehensive diagnostic process carried out by WSP (2025), incorporating geotechnical analyses, hydrological and geochemical evaluations, ecological assessments, and stakeholder expectations. The methodology follows the principles of ABNT NBR 13.029:2024 – focused on integrated and progressive planning – as well as international references such as ICMM (2025).

The closure objectives for PDE Sul were based on the requirements of ABNT NBR 13.029:2024 and the ICMM (2025) guidance for integrated mine closure. They also reflect WSP (2025) technical recommendations, incorporating diagnostic results and stakeholder-defined priorities.

The main closure objectives established for PDE Sul are summarised below, each grounded in site-specific diagnostics and aligned with regulatory and stakeholder expectations:

- Ensuring long-term geotechnical stability, by preventing slope failures, structural deformations, and erosion through slope reconfiguration, berm implementation, and stability modelling techniques (e.g. Spencer and Morgenstern-Price methods).
- Controlling hydrological dynamics by designing robust drainage infrastructure (e.g. toe drains, surface channels, and energy dissipators) capable of operating under probable maximum precipitation (PMP) conditions.
- Preventing adverse geochemical processes, particularly ARD, by identifying and isolating potentially acid-generating materials through ABA and humidity cell tests, ensuring leachate concentrations remain compliant with CONAMA Resolution 420/2009, which establishes that the protection of soil must be carried out preventively, in order to ensure the maintenance of its functionality or, in a corrective manner, aiming to restore its quality or recover it in a way compatible with the intended uses.
- Rehabilitating the area ecologically, through the establishment of a self-sustaining vegetative cover composed of native species with deep root systems, contributing to slope stability, evapotranspiration regulation, and habitat formation.
- Preparing the site for future compatible land uses, defined by Vale's internal land use zoning strategy, specifically within the 'zone of re-signification', ensuring integration with local ecological corridors and landscape units.
- Fostering social and regulatory acceptance by promoting stakeholder engagement, demonstrating compliance with licensing conditions, and embedding a transparent, auditable monitoring programme into the closure process, in alignment with ICMM (2025) and Vale's strategy.

These objectives provide the strategic basis for coherence across all components of the PDE Sul closure plan. These goals not only reflect a synthesis of regulatory expectations and environmental standards but are deeply rooted in the technical diagnostics and geotechnical realities of the site. Their compatibility with the guidelines of ABNT NBR 13.029:2024, the best practice principles of the ICMM (2025), and the geotechnical and environmental philosophy presented by WSP (2025) illustrates a high degree of alignment and integration.

In this sense, the objectives outlined provide a foundation not only for the current phase of conceptual planning but also for future basic and executive designs, monitoring frameworks, stakeholder communication strategies, and compliance pathways. They reinforce closure planning as a core element of sustainable mine life cycle management, beyond regulatory compliance. PDE Sul thus becomes a reference case for how rigorously defined objectives—when informed by diagnostics, norms, and good practices—can direct a technically sound, environmentally justifiable, and socially accepted closure strategy.

6 Implementation measures to achieve closure success criteria

The closure measures implemented at PDE Sul put into practice the success criteria defined in Section 4 and the objectives established in Section 5. These three elements (criteria, objectives and implementation) are interrelated and structured to promote continuity, informed decision-making and long-term performance. The strategy developed by WSP (2025), in the technical report (RL-1190JJ-X-15131) about the conceptual closure plan for the South Waste Rock Pile (PDE Sul), reflects this approach by converting performance targets into concrete, multidisciplinary actions aligned with both national and international standards, including ABNT NBR 13.029:2024 and ICMM (2025).

> *"Establishes performance criteria for closure that ensure the long-term physical, chemical and ecological stability of waste rock piles, integrating engineering, environmental and social aspects into the planning and implementation process." ABNT NBR 13.029 (ABNT 2024a)*

Each group of measures presented below corresponds to specific dimensions of the success criteria. This connection helps align the technical design with the intended outcomes and contributes to effective long-term monitoring and adaptive management.

To fulfill the success criteria established for the closure of the PDE Sul waste rock dump, the conceptual plan includes a comprehensive set of engineering, environmental, and ecological measures. These measures were defined based on site-specific diagnostics, incorporating geotechnical analyses, hydrological assessments, and geochemical characterisation to ensure technical robustness and contextual relevance. The interventions are structured according to five key performance dimensions:

- Geotechnical stability: slope reprofiling is planned to achieve inclinations compatible with long-term static and dynamic stability, in line with ABNT NBR 13.029:2024, which requires FoS ≥ 1.5. The conceptual design, developed by WSP (2025), also follows methods recommended by Hawley & Cunning (2017), integrating deposition geometry and foundation behaviour into stability modelling. Berms and benches will serve as energy dissipators and slope segmentation features. In more vulnerable zones, compacted inert material covers will enhance mass balance and reduce infiltration.
- Hydrological performance: the design includes continuous surface channels to collect and direct runoff toward designated sedimentation basins. Drainage channels will be lined or vegetated depending on slope and flow velocity, and energy dissipation structures (such as rock aprons) will be placed at outlets. Hydrological modelling supported the dimensioning of the drainage system, taking into account historical rainfall data and PMP scenarios.
- Geochemical containment: the closure system integrates findings from ABA and humidity cell tests to isolate potentially acid-generating materials. The multilayer cover system – comprising a compacted clay barrier, capillary break, and growth medium – is designed to reduce oxygen and water ingress, thereby minimising ARD generation and metal mobility. These measures align with CONAMA Resolution 420/2009 for soil and water quality.
- Ecological and landscape integration: in accordance with the ICMM (2025) and Vale's environmental restoration strategy, native species with hydromechanical function and local resilience were selected for revegetation. Hydroseeding and direct planting techniques will ensure functional root systems, supported by soil amendments and micro-nutrient treatments. The visual integration into the landscape complements broader ecological corridor connectivity, as outlined in the PDE Sul zoning plan as established in the technical report prepared by WSP in 2025.

- Monitoring and adaptive management: implementation of a dedicated monitoring network is essential to evaluate compliance with success criteria. This includes real-time instrumentation such as piezometers for water level tracking, inclinometers for stability verification, and NDVI surveys for vegetative recovery. Data generated will inform responsive adjustments throughout the closure timeline. This monitoring framework gives operational continuity to the criteria outlined in Section 4.4, supporting adaptive decision-making in accordance with ABNT NBR 13.029:2024, ICMM (2025), and Vale's internal governance model.

The set of combined measures represents an integrated approach that aligns with international best practices and Brazilian regulatory standards, while also being adapted to the specific challenges and opportunities of the PDE Sul site. Their implementation is planned in stages and will be incorporated into a broader site recovery programme that considers the legacy of the Córrego do Feijão complex.

The implementation framework for PDE Sul offers a technically consistent and regulatory-compliant path from conceptual planning to field execution. Each design component was developed to meet at least one success criterion, taking into account the site's operational history and current limitations. This reinforces the coherence and robustness of the closure strategy. Rather than approaching closure as a set of isolated tasks, the PDE Sul case adopts a continuous and systemic perspective, aligning diagnostics, objectives, actions and monitoring. This strategic consistency, grounded in best practices, informed by site-specific analyses and supported by disciplined execution, positions the PDE Sul waste rock dump as a reference for progressive mine closure in complex operational and environmental contexts.

7 Post-closure monitoring and data interpretation timeline

To illustrate the monitoring strategy adopted for PDE Sul and support the adaptive management approach, a phased timeline of post-closure data interpretation activities is presented in Table 2 and Figure 5. This timeline aligns with the closure framework developed by WSP (2025) and complies with the guidelines established by ABNT NBR 13.029:2024 and ICMM (2025).

According to ABNT NBR 13.029:2024, the conceptual closure plan must include all activities following the end of the operational life of the waste pile, aiming at its integration into the environment and enabling its future use.

Table 2 Post-closure monitoring and data interpretation timeline

Phase	Time frame	Key activities	Purpose
Phase 1	0–6 months post-closure	Instrument calibration, baseline validation, and first data collection cycle	Establish reference conditions and verify system readiness
Phase 2	6–24 months	Quarterly data collection (geotechnical, hydro, chemical, ecological), trend identification	Detect early deviations, confirm short-term performance, and apply minor corrections if needed
Phase 3	2–5 years	Annual evaluations, detailed analysis of seasonal and long-term behaviour across all criteria	Support adaptive responses, identify medium-term trends, validate assumptions
Phase 4	5–10 years	Biennial technical audits and cumulative interpretation of monitoring data	Demonstrate consolidation of closure measures, provide evidence for regulatory and institutional reviews

Phase	Time frame	Key activities	Purpose
Phase 5	>10 years	Long-term surveillance, reduced-frequency monitoring; handover documentation	Confirm legacy performance, support land use transition, finalise institutional knowledge transfer

The structured timeline allows performance interpretation to evolve in parallel with field conditions. It integrates the technical foundation of the WSP (2025) closure plan with the ongoing requirements for compliance, transparency, and accountability expected by regulatory bodies and stakeholders.

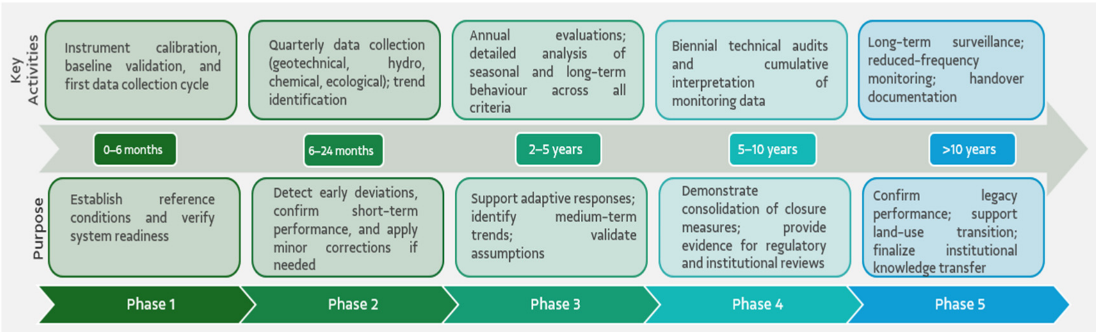

Figure 5 Post-closure monitoring timeline

The effectiveness of a mine closure strategy is best demonstrated by its capacity to endure long-term field validation. In the case of the PDE Sul waste rock dump, data interpretation plays a central role in verifying whether the conceptual objectives (Section 5) and success criteria (Section 4) are being achieved through the implemented measures (Section 6). This stage of interpretation reinforces the feedback loop required to maintain sustainability, compliance, and resilience across environmental and geotechnical domains.

The monitoring programme developed by WSP (2025) comprises structured data collection targeting geotechnical stability, hydrological behaviour, chemical safety, and ecological recovery. Supported by geospatial tools and field-based analysis, this system enables the continuous evaluation of closure performance indicators, in alignment with ABNT NBR 13.029:2024, ICMM (2025).

The key domains addressed through data interpretation are as follows:

- Geotechnical indicators: UAV-based topographic surveys, inclinometer readings, and surface inspections assess slope deformation and berm performance. Interpretation is based on thresholds defined in WSP's design models using limit equilibrium methods (e.g. Spencer, Morgenstern-Price).
- Hydrological metrics: flow volumes, water retention, and sediment transport are analysed against hydrological design predictions and rainfall-frequency modelling benchmarks. Erosive trends are reviewed in light of GARD Guide and NBR 13.029 expectations for long-term drainage integrity.
- Geochemical performance: water samples from monitoring wells and surface discharge points are analysed for pH, electrical conductivity, and metal concentrations, ensuring ongoing compliance with CONAMA Resolution 420/2009. Longitudinal trend analysis validates the effectiveness of encapsulation and cover layers.
- Ecological recovery: NDVI values, species richness, and soil conditions are compared to baseline ecological targets, validating native species establishment, slope stabilisation through root mass development, and long-term vegetation sustainability.

Data interpretation at PDE Sul follows a SMART-based approach, generating information not only for regulatory compliance and stakeholder engagement, but also for real-time decision-making in adaptive management. As trends are identified, results are visualised through dashboards and assessed against predefined thresholds to confirm performance or trigger corrective actions.

This approach positions monitoring as an active tool for governance and technical oversight, rather than a passive reporting function. By aligning with the principles of ICMM (2025), ABNT NBR 13.029:2024, and WSP's (2025) technical report (RL-1190JJ-X-15131), the PDE Sul project emphasises that successful closure depends not only on sound design, but also on continuous validation and institutional learning. It is this ability to respond to evolving data that strengthens the long-term environmental and social legacy of the structure.

8 Conclusion

The closure strategy implemented for the PDE Sul waste rock dump stands as a reference model for integrated, technically sound, and regulation-compliant mine closure. Developed by WSP (2025), the project addresses strategic closure objectives into measurable outcomes through a multidisciplinary approach.

From the outset, the closure plan was aligned with recognised national standards, addressing key areas such as geotechnical stability, hydrological control, chemical safety, ecological restoration, and institutional governance. It also drew on international best practices, including the ICMM's *Integrated Mine Closure: Good Practice Guide* (ICMM 2025) and methodologies by Hawley & Cunning (2017). These standards guided the definition of success criteria such as slope regrading, engineered drainage systems, revegetation with native species, and a robust monitoring program.

This study mainly demonstrates how SMART-aligned success criteria can be embedded in a phased and auditable closure program. A continuous monitoring framework, supported by adaptive feedback, ensures both regulatory compliance and long-term performance management. Further, by integrating planning, execution, and verification into a single coherent framework, the project sets a replicable precedent for the progressive closure of legacy waste rock dumps in Brazil and beyond.

This paper highlights driving the following measures for closure strategy:

- Deepen integration across technical subjects (geotechnical, hydrological, geochemical, and revegetation), emphasising system-wide interactions.
- Define clear monitoring thresholds linked to corrective actions and adaptive governance protocols.
- Expand revegetation indicators to include functional metrics such as biomass, infiltration capacity, and faunal return.
- Reflect on cost-effectiveness and optimise the allocation of asset retirement obligation funds to ensure economic sustainability.
- Establish institutional knowledge management systems to support technical continuity and long-term governance.

These enhancements would improve the resilience, transparency, and replicability of future closure initiatives, aligning with evolving global expectations for sustainable mine closure.

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