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A critical assessment for reclamation of the waste dumps at Águas Claras mine under Brazilian regulatory standards

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Abstract

Águas Claras mine in southeastern Brazil had its activities ceased in late 2002 after 29 years of high-grade iron ore exploitation. Since then, actions have been carried out to close the mine and reduce the risks related to more than 60 Mm³ of mine waste stored in dumps surrounding the mine. Although already revegetated and integrated into the environment, the waste dumps present in some cases Factors of Safety (FoS) lower than the values established by the new standards of the Brazilian regulatory agencies (FoS ≥ 1.5), which would require geometry adjustments (reshaping or buttressing), in addition to surface drainage improvements, to meet the criteria for reclamation and post-mining land use. To support decision-making and define actions for physical stabilisation and closure, a risk-based method was chosen over the conventional 'minimum FoS' approach. The 'residual risk rating' index (R^3) proposed by Hawley et al. (2024) and updated by de Graaf et al. (2025) was applied to define a target stability reliability (TSR), assessing design confidence levels, the 'waste dump hazard class' (WHC), and the consequences of a potential failure. According to Hawley et al. (2024), three of the five dumps evaluated obtained a moderate level of R^3, demanding a FoS close to the range required by current Brazilian standards (1.3 < FoS ≤ 1.5), while two of them obtained a high and a very high level, which means rigorous analyses and higher FoS are recommended for closure (1.5 < FoS ≤ 1.8 and 1.8 < FoS ≤ 2.0, respectively). However, when following the model updated by de Graaf et al. (2025), four dumps fell into the high-risk category, requiring a FoS ≥ 1.5, and one of the dumps obtained a very high R^3 level (FoS ≥ 1.7 suggested). The 2025 framework proved to be more conservative than the 2024 version, grouping dumps of varying WHCs and failure consequences into the same high-risk category. The adoption of an FoS higher than those defined by the Brazilian standard (NBR) 13029/2024, resulting in greater interventions for closure, should be evaluated considering technical, economic and environmental feasibility, also accounting for the advanced state of recovery and integration of the dumps into the environment. Ideally, minimum adjustments should be made to meet the criteria established by current Brazilian standards and actions taken to increase confidence level and ensure the maintenance of these values in a long-term scenario. The results demonstrate the importance of defining a TSR for closure while still in the operational phase, enabling the use of available resources, reducing costs and avoiding issues related to environmental and third part organisations after deactivation of the waste dumps. The approach discussed in this paper offers a practical benchmark for future reclamation efforts and contributes to the development of more adaptive, risk-based closure policies.

Keywords: *mine closure, reclamation, waste dumps, Factor of Safety, performance assessment*

1 Introduction

The Águas Claras mine, located along the southeastern flank of Serra do Curral (historical, environmental and cultural heritage of the city of Belo Horizonte, Minas Gerais) in southeastern Brazil ceased its activities at the end of 2002, after almost 30 years of high-grade iron ore mining. The mine is situated on the northwestern edge of the iron quadrangle (one of the world's most important mineral provinces) and represents a milestone in the Brazilian mineral industry, not only for its industrial scale and the innovative technologies

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employed at the time, but mainly for the high grade of its ore and the operational procedures adopted to enable mining activities close to a large urban centre.

Figure 1 shows a panoramic view of the open pit at the end of its operations in 2022, where it is possible to see the top of Serra do Curral and the city of Belo Horizonte in the background.

Figure 1 Panoramic view of the open pit in 2002 (from Vale S.A. historical files)

Over the mine's lifespan, it is estimated that approximately 290 Mt of high-grade iron ore (on average 68% Fe), locally referred to as 'hematite', were extracted and more than 150 Mt of mine waste were generated (a widely graded heterogeneous mixture of coarse and fine particles, ranging from silt to boulders and fragments of rock), most of which were disposed of in dumps built in the valleys and side-hills south of the open pit, with heights of up to 200 m.

Since the end of operations, actions have been carried out to close the mine and to reduce the risks related to the remaining geotechnical assets, including the waste dumps. However, despite being completely revegetated and integrated into the environment, these dumps have in some cases Factors of Safety (FoS) lower than the values established by the Brazilian regulatory agencies new standards (FoS ≥ 1.5), which would require geometry adjustments (reshaping or buttressing) to meet the criteria established for reclamation and post-mining land use. Some waste dumps have an FoS lower than 1.2.

The lack of objective guidelines and new regulatory criteria, in addition to the small number of successful case studies published in Brazil, makes the closure and reclamation of waste dumps still a little-known subject in the local mining industry. One of the main references in the country is the Guide for Mine Closure Planning (Sánchez et al. 2014) issued by the Brazilian Mining Association (IBRAM) which, despite presenting fundamental guidelines and best practices for mine closure, doesn't include specific geotechnical criteria.

Therefore, in order to assess the safety and stability performance of the waste dumps, assisting in decision-making and defining appropriate actions for physical stabilisation and closure, a more comprehensive risk-based methodology was adopted instead of the conventional 'minimum FoS' approach typically used by regulators. The methodology is based on the residual risk rating index (R^3) proposed by Hawley et al. (2024) and updated by de Graaf et al. (2025), which incorporates the level of confidence in the input parameters and available data, the severity of potential failure consequences, and the waste dump stability rating and hazard classification (WSRHC) system introduced by Hawley & Cunning (2017). The resulting R^3 index is then used to define a target stability reliability (TSR) for closure in accordance with the 'as low as reasonably possible' (ALARP) principle and stakeholders' expectations.

A brief overview of the evolution of Brazilian regulations regarding waste dumps is also provided and the TSR defined by both versions (2024 and 2025) through the R³ index is compared to the criteria established by the regulators, i.e. a fixed minimum FoS threshold, without accounting for varying levels of risk and uncertainty. The actions recommended by Hawley et al. (2024) and de Graaf et al. (2025) are also assessed considering their applicability to the closure of the waste dumps at Águas Claras mine.

2 Waste dumps at Águas Claras Mine

The mine waste generated over almost 30 years of operation of the Águas Claras mine was disposed of in five main dumps built in the valleys and side-hills to the south of the open pit (Figure 2). Locally, the waste dumps are referred to as 'Grotas' and are numbered from southwest to northeast as Grota -1, Grota 0, Grota 1, Grota 2 and Grota 3.

It is worth mentioning that Grota -1 is not officially classified as a waste dump since its construction was not intended to store mine waste but rather to fill up a valley and enable the construction of an operational access (side-hill fill). However, as in practice and for stability purposes there's no distinction, in this paper Grota -1 is also being treated as a waste dump. The descending construction method (end dumping) may have led to a steeper overall slope angle.

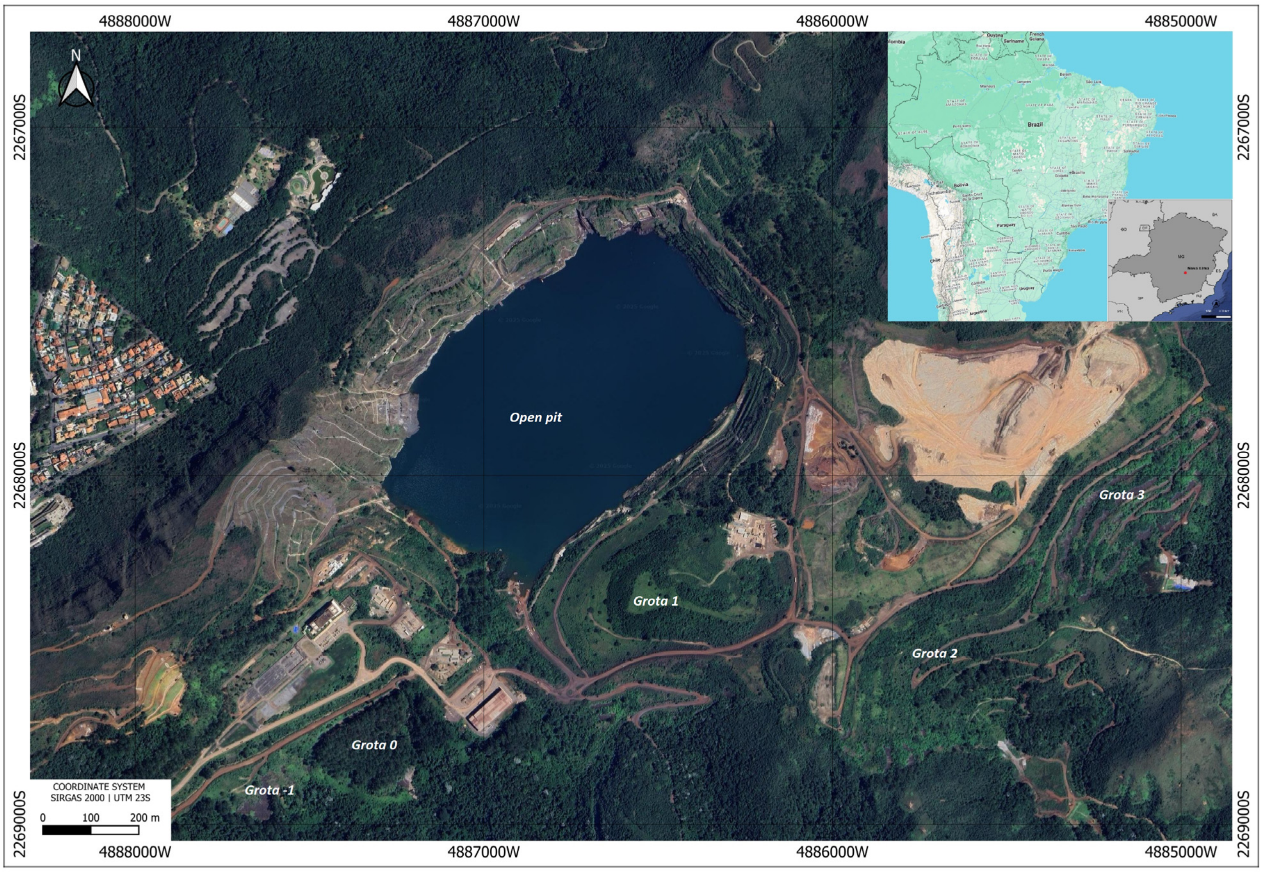


Figure 2 Location of the waste dumps at Águas Claras mine

The waste material generated at the mine was composed predominantly of phyllite, quartzite and dolomite and, secondarily, of itabirite in different degrees of alteration, resulting in a heterogenous silt-sandy or sandy-silty matrix with the presence of boulders and rock blocks. Typical values of friction angle range from 26–34°, depending on the percentage of fines, while cohesion values usually range from 0–15 kPa. The waste material is chemically inert and less prone to acid generation and metal leaching.

The foundation of these dumps is basically composed of residual soils (W6) and weathered rocks (W3–W5) of quartzite, schist and phyllite.

Águas Claras mine was acquired already inactive in the early 2000s, with the waste dumps in their final configuration, already revegetated and integrated into the environment (Figure 3). Built between the 1970s and the late 1990s, these dumps lack detailed records of their original designs and operational performance. As a result, several investigation programs have been conducted over the past decade in order to better characterise their foundations and stability conditions. While the absence of original designs may affect confidence levels, it doesn't necessarily compromise the safety of the dumps.

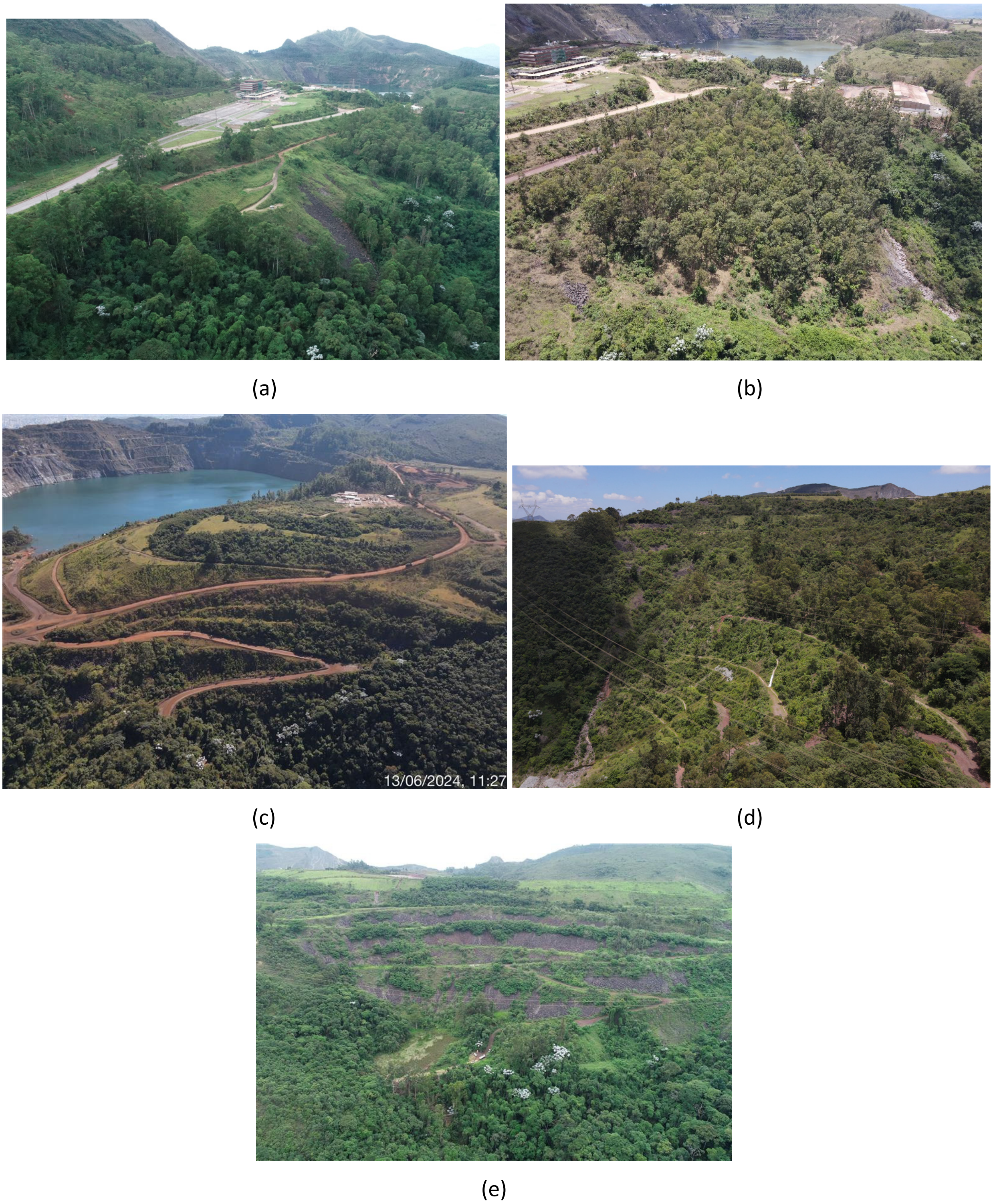


Figure 3 Waste dumps at Águas Claras mine. (a) Grota -1; (b) Grota 0; (c) Grota 1; (d) Grota 2; (e) Grota 3

As shown in Figures 3a, b and e, at the time of operations, some of the waste dumps were buttressed by rock blocks in order to help controlling erosion, improving internal and surface drainage and increasing the overall stability.

Table 1 shows the main information and features of the waste dumps (‘Grotas’) including their current FoS (2D) calculated by the limit equilibrium method.

Table 1 Waste dumps main features

Waste dump	Construction date	Construction method	Height (m)	Overall slope angle (°)	Volume (m^3) [2]	Factor of Safety	Performance	Monitoring type	Facilities/ areas downstream
Grota -1	1990s	Descending	~90	32	1.2 × 10^5	1.09	Good. No history of deformations/settlements over the last decade. Very rare shallow silver failures during the rainy season.	2 PZs [3] 4 Prisms	RPPN [4] Mata do Jambreiro
Grota 0	1984–1987	Ascending	~120	23	2.7 × 10^6	1.23	Good. Besides a shallow local failure and some small erosive processes happened during the extreme rainy season of 2020, the dump has no history of deformations/settlements or instabilities.	6 PZs	RPPN Mata do Jambreiro
Grota 1	Phase 1: 1973–1984 Phase 2: 1987–1995	Ascending	~150	25	2.2 × 10^7	1.58	Good. No history of deformations/settlements over the last decade. Very rare small failures during the rainy season.	10 PZs	Mine’s main road
Grota 2	1980s–1998	Ascending	~190	21	3.5 × 10^7	1.30	Fair. History of small shallow failures during the rainy season, in addition to some minor deformation and local uncontrolled seepage near the toe of the dump.	24 PZs 5 Prisms	Dam 7A and Dam 7B (sediment containment)
Grota 3	1976–1998	Hybrid [1]	~200	27	4.2 × 10^7	1.17	Good. No history of deformation/settlement over the last decade. Rare small failures during extreme rains.	14 PZs 17 Prisms	Dam 6 (sediment containment)

Notes: 1) Combination of descending and ascending. 2) Volumes calculated considering a bulking factor of 1.35. 3) Standpipe piezometers. 4) RPPN is the Portuguese acronym for Private Natural Heritage Reserve, a conservation unit established voluntarily on private lands, legally recognised by federal, state and local governments to conserve biological diversity without expropriating the owner.

3 Residual risk rating index (R^3)

As detailed in Carter et al. (2022) and Hawley et al. (2024), design acceptance criteria (DAC) defined for initial design studies and operations may not be appropriate for closure. During closure phase, the confidence in the available data and information may have increased, the risk tolerance for instabilities will probably be lower and the failure mechanisms assumed to control stability during design and operations may differ significantly from those that control long-term physical stability.

In that sense, the selection of closure criteria applied to ensure long-term physical stability of waste dumps should be based on a comprehensive analysis of risk tolerance, considering the potential consequences of a possible failure, the level of confidence in the input parameters and in the geological model, as well as stakeholders’ expectations and post-mining land use (Hawley et al. 2024).

Defining a fixed minimum FoS threshold as DAC for closure, without accounting for the inherent variability and uncertainty in geotechnical conditions and performance, although complying with typical Brazilian regulatory requirements, seems to be a too simplistic approach, potentially overlooking the complexity of long-term stability and leading to inadequate risk mitigation measures. A risk-based approach considering the influence of site-specific factors provides a more realistic and defensible basis for decision-making and mitigation planning, aligning better with the principles of sustainable closure and long-term public and environmental safety.

As presented by Hawley et al. (2024), a risk-based approach such as that incorporated in the relative stability guideline (RSG) and TSR methodology proposed originally by Carter et al. (2022) for open pits offers a systematic method for evaluating acceptability criteria for closure, considering the perspectives of different stakeholders. The RSG methodology would also be well aligned with the current industry philosophy for overall risk management and closure objectives.

These authors updated the original RSG methodology enabling its application for waste dumps. The 'slope condition class', previously called 'wall stability condition class' and divided into a seven-step scale, was replaced by a five-step scale in order to correspond to the 'waste dump stability and hazard class' (WHC) proposed by Hawley & Cunning (2017). This system provides a detailed framework for classifying mine waste dumps and assessing their relative potential for instability, incorporating key factors such as foundation conditions, construction methods, stability and performance.

For the 'slope condition class' and the 'failure consequence' categories, Hawley et al. (2024) assigned numerical values to each class ranging from 1 to 5. For the 'design confidence' category, the numerical values range from 1 to 4, with the 'very low' and 'low' classes being assigned equal values of 4. The original RSG nomenclature has been replaced by a new index, named 'residual risk rating' (R^3), calculated as the product of the three component indices (Equation 1). The maximum value for the 'design confidence' index was limited to 4 to achieve a maximum possible normalised score of 5 × 4 × 5 = 100 (worst case scenario), replacing the previous RSG matrix score of 7 × 5 × 5 = 175. Capping the maximum score at 100, instead of 175, makes interpreting the results more straightforward and intuitive. The minimum possible R^3 score (best case scenario) by the new revised system is 1 (Figure 4).

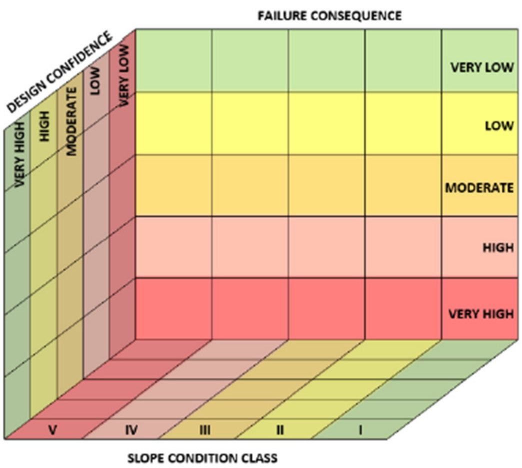
$$R^3 = Cf \times Cq \times Cl \tag{1}$$

where:

Cf = confidence rating (between 1 and 4)

Cq = consequence rating on a scale of 1 to 5

Cl = slope condition class, defined on a scale of 1 to 5 according to the WHC.



EXISTING CONDITION RANKING				
SLOPE CONDITION CLASS			Design Confidence Rating	Failure Consequence Rating
SCC	WSC	Rating		
V	V	VH = 5	VL = 4	VH = 5
IV	IV	H = 4	L = 4	H = 4
III	III	M = 3	M = 3	M = 3
II	II	L = 2	H = 2	L = 2
I	I	VL = 1	VH = 1	VL = 1

	R^3 Score
	80-100
	60-80
	40-60
	20-40
	<20

Figure 4 Residual risk rating (R^3) matrix for open pits and waste dumps (Hawley et al. 2024)

This methodology involves defining an initial R^3 value as a basis for suggesting a TSR, followed by an iterative process to improve the score, where the geometric configuration for closure of the waste dump should be modified or the confidence level increased through further investigations and complementary studies. According to the authors, the R^3 values should then be updated and the process repeated as necessary until all stakeholders agree that the solution meets ALARP objectives. For example, probabilistic analyses could be performed in order to account for the great variability of mine waste shear strength parameters, increasing the design confidence level and reducing the R^3 index.

Table 2 presents the suggested TSR criteria (FoS or Probability of Failure [PoF]) and associated closure actions proposed by Hawley et al. (2024) based on the initial R^3 score.

Table 2 Recommended target stability reliability (TSR) criteria actions based on initial R^3 score for open pits and waste dumps (adapted from Hawley et al. 2024)

R^3 score	R^3 level	Suggested TSR static Factor of Safety (FoS)*	Recommended actions
$R^3 > 80$	Extreme	FoS > 2 PoF < 0.5%	Comprehensive and rigorous analysis required to develop a deep understanding of failure mechanisms and behaviour to support implementation of very robust controls. Detailed numerical crest breakback and/or runout analyses to establish permanent exclusion zones. Likely requires detailed supplementary field and laboratory investigations. Detailed evaluation of feasibility of alternatives/trade-off studies to reduce R^3 and achieve ALARP objective. Very high design reliability required. FoS >2 needed unless quantitative risk assessment (QRA) is undertaken
$60 \leq R^3 \leq 80$	Very High	1.8 < FoS ≤ 2.0 PoF < 0.75%	
$40 \leq R^3 < 60$	High	1.5 < FoS ≤ 1.8 PoF < 1%	Rigorous analysis necessary, so that thorough understanding of mechanisms is obtained and robust controls can be implemented. Detailed numerical runout analyses to establish permanent exclusion zones. May require supplementary field and laboratory investigations. Trade-off studies to assess the feasibility of reducing R^3 score and achieving ALARP objective. High design reliability required. FoS > 1.5
$20 \leq R^3 < 40$	Moderate	1.3 < FoS ≤ 1.5 PoF < 1.5%	Moderate level of reliability of all critical inputs required to support stability analysis. Standard analysis and/or empirical approaches sufficient. Good understanding of the scenario is needed so that appropriate controls can be implemented. Empirical breakback and/or runout analyses to establish permanent exclusion zones. May require supplementary field and laboratory investigations. Confirm alignment with ALARP objective. Good design reliability required. FoS > 1.3
$R^3 < 20$	Low	1.2 < FoS ≤ 1.3 PoF < 3%	Evaluate reliability of all critical inputs to support stability analysis. Apply good practice, guidance, and hierarchy of controls. May require targeted investigations to address areas where knowledge is lacking or unreliable. Confirm alignment with ALARP objective. Fair design reliability required. FoS > 1.2

*For relinquishment and passive closure objectives; one class lower for active closure or ongoing 'care and maintenance' objectives (FoS 1.2 minimum).

The initial guidance provided by Hawley et al. (2024) for interpretating the R^3 score and for defining preliminary TSR for closure of waste dumps was revisited and updated by de Graaf et al. (2025) in the recently published *Guidelines for Open Pit and Waste Dump Closure*, as presented in Table 3.

The main changes in the updated guidance are:

- The minimum FoS suggested for closure of waste dumps with very high R^3 scores ($60 \leq R^3 < 80$) is now 1.7, instead of 1.8 < FoS ≤ 2.
- The high level range was expanded and now comprises waste dumps with $30 \leq R^3 < 60$, i.e. waste dumps with $30 \leq R^3 < 40$ that previously fell into the moderate level category are now classified as high level, with a minimum FoS of 1.5 suggested as TSR.
- The moderate level now comprises waste dumps with $10 \leq R^3 < 30$, i.e. waste dumps with $10 \leq R^3 < 20$ that previously fell into the low-level category are now classified as moderate level, with a minimum FoS of 1.3 being suggested for closure.
- The low-level category was narrowed and now comprises only waste dumps with $R^3 < 10$.

It is worth noting that, although the R^3 level thresholds and corresponding FoS have been revised, the associated probabilities of failure (PoF) and recommended closure actions remained unaltered.

Table 3 Updated recommended target stability reliability (TSR) criteria actions based on initial R^3 score for open pits and waste dumps (adapted from de Graaf et al. 2025)

R^3 score	R^3 level	Suggested TSR static Factor of Safety (FoS)*	Recommended actions
$R^3 \geq 80$	Extreme	FoS ≥ 2 PoF < 0.5%	Comprehensive and extremely rigorous analysis required to develop deep understanding of failure mechanisms and behaviour to support implementation of extremely robust controls. Detailed numerical crest breakback and/or runout analyses to establish permanent exclusion zones. Likely requires detailed supplementary field and laboratory investigations. Detailed evaluation of feasibility of alternatives/trade-off studies to reduce R^3 and achieve ALARP objective. Very high design reliability required. FoS ≥ 2 needed unless quantitative risk assessment (QRA) undertaken.
$60 \leq R^3 < 80$	Very High	FoS ≥ 1.7 PoF < 0.75%	
$30 \leq R^3 < 60$	High	FoS ≥ 1.5 PoF < 1%	Rigorous analysis necessary, so that thorough understanding of mechanisms is gained, so robust controls can be implemented. Detailed numerical runout analyses to establish permanent exclusion zones. May require supplementary field and laboratory investigations. Trade-off studies to assess feasibility of reducing R^3 and achieving ALARP objective. High design reliability required. FoS ≥ 1.5
$10 \leq R^3 < 30$	Moderate	FoS ≥ 1.3 PoF < 1.5%	Moderate level of reliability of all critical inputs required to support stability analysis. Standard analysis sufficient (empirical approaches), good understanding needed of scenario so that appropriate controls can be implemented. Empirical breakback and/or runout analyses to establish permanent exclusion zones. May require supplementary field and laboratory investigations. Confirm alignment with ALARP objective. Good design reliability required. FoS ≥ 1.3
$R^3 < 10$	Low	FoS ≥ 1.2 PoF < 3%	Evaluate reliability of all critical inputs to support stability analysis. Apply good practice, guidance, and hierarchy of controls, may require targeted investigations to address areas where knowledge is lacking or unreliable. Confirm alignment with ALARP objective. Fair design reliability required. FoS ≥ 1.2

*For relinquishment and passive closure objectives; one class lower for active closure or ongoing 'care and maintenance' objectives (FoS 1.2 minimum).

The TSR suggested by Hawley et al. (2024) and de Graaf et al. (2025) for closure of each waste dump at Águas Claras mine will be compared to the minimum FoS threshold required by the Brazilian standards (FoS ≥ 1.5) and recommended closure actions further discussed.

4 Brazilian regulations for mine waste dumps

Published on 30 July 1993 by the Brazilian Association of Technical Standards (ABNT), the first national standard for mine waste dumps (NBR 13029) set the minimum design requirements for waste dumps generated from open pit and underground mining, aiming to ensure safety, operability, cost-effectiveness and environmentally responsible abandonment or post-mining land use (Associação Brasileira de Normas Técnicas 1993).

The waste dumps at Águas Claras mine were built between 1973 and 1998 (Table 1), mostly before the first regulatory standards were published. With no original design documents available, it's believed that despite having followed best engineering practices of the time, the construction of these dumps likely focused on operational safety and cost optimisation, without much consideration regarding long-term physical stability.

Although pioneering, the first edition of NBR 13029 faced criticism from the local industry at the time for not setting minimum values for FoS (operational or closure) or clear stability analysis criteria. Furthermore, despite defining some geometric parameters such as maximum dump height and slope angles, some of these specific recommendations lacked proper technical justification.

The standard also mentioned that design documents should include deactivation measures to ensure the waste dump's safe and non-polluting condition, minimising maintenance and allowing its full integration into the local environment after closure.

The second edition of NBR 13029 was published on 4 September 2006 and defined, for the first time, the minimum FoS for both global and local instabilities of mine waste dumps (Table 4). According to this edition, a deactivation plan should be presented whenever post-mining land use was defined and/or specific legislation applied.

Table 4 Minimum Factors of Safety according to NBR 13029/2006 (adapted from Associação Brasileira de Normas Técnicas 2006)

Global failure	Minimum Factor of Safety
Normal phreatic surface*	1.50
Critical phreatic surface**	1.30
Local failure	**Minimum Factor of Safety**
Between benches	1.50

*Acceptable phreatic surface for normal internal drainage operating conditions.
**Maximum acceptable phreatic surface for conditions in which the internal drainage is not working as designed.

The third edition of NBR 13029, published on 24 July 2017, distinguished between deactivation, now defined as the end of construction of the waste dump, i.e. the end of its operational life, and closure, defined as its integration into the environment and readiness for post-mining land use. This edition also required that the design should include a conceptual decommissioning plan addressing post-operational activities such as monitoring, instrumentation, surface cover, drainage and physical stability assurance. A conceptual closure plan should also be provided whenever post-mining land use was defined and/or specific legislation applied. No further details were specified. The 2017 revision established different minimum values of FoS for local instabilities of slopes composed predominantly of rock material and those composed of soil (Table 5).

Table 5 Minimum Factors of Safety according to NBR 13029/2017 (adapted from Associação Brasileira de Normas Técnicas 2017)

Global failure	**Minimum Factor of Safety**
Normal phreatic surface*	1.50
Critical phreatic surface**	1.30
Local failure (between benches)	**Minimum Factor of Safety**
Soil slope	1.50
Rock slope	1.30

*Acceptable phreatic surface for normal internal drainage operating conditions.
**Phreatic surface that introduces critical stability conditions due to non-functioning of the internal drainage.

The fourth and most recent revision of NBR 13029, published on 8 August 2024, recommends prioritising progressive dump closure during mine operations (when possible), incorporating surface covers appropriate to local vegetation and anticipated post-mining land use. The conceptual closure plan now includes the deactivation plan, covering all post-operational activities and ensuring physical and chemical stability.

Regarding physical stability, NBR 13029/2024 no longer distinguishes between normal and critical watertable conditions for FoS calculations. However, it now differentiates between operational slopes (temporary geometry) and final slopes (design geometry). The FoS for the final geometry could be understood as the value suggested for closure (Table 6).

Table 6 Minimum Factors of Safety according to NBR 13029/2024 (adapted from Associação Brasileira de Normas Técnicas 2024)

Stability assessment	**Slope configuration**	
	Operational	**Final**
Global failure	1.5	1.5
Local failure (between benches) *	1.3	1.5

* For rock slopes which mass resistance is essentially controlled by the interaction between the blocks, the minimum Factor of Safety for the final geometry can be 1.3.

NBR 13029/2024 emphasises that due to the heterogeneity of waste dumps, the minimum FoS suggested from limit equilibrium analysis should be one criterion among others, and not the sole determinant of the overall safety of the dump. It should be supplemented by inspections, risk analyses and appropriate engineering judgment. This statement was a first step in acknowledging the uncertainties associated with assessing waste dumps' safety based solely on a single minimum FoS threshold. Nonetheless, the FoS is still the main criterion assessed by regulators.

It's important to highlight that none of the editions address older waste dumps, already inactive and, in some cases, fully recovered, which sometimes don't meet the established minimum FoS. For these waste dumps, a more comprehensive risk-based approach, considering performance, level of confidence and overall safety conditions, would seem to be more appropriate, especially for closure. However, the obligation to meet the criteria defined by the standards, regardless of the risk level and post-mining land use, still remains a challenge.

As pointed out by Carter et al. (2022), one of the concerns with directly applying typical operational FoS criteria to mine closure acceptance thresholds is that such limits do not reliably reflect the PoF, especially where data uncertainty is high.

5 Results and discussions

5.1 Waste dumps' R^3 score calculations

To calculate the initial R^3 score, each dump was first classified according to the WSRHC system proposed by Hawley & Cunning (2017) based on a scoring framework that considers regional context factors, foundation characteristics, waste material quality, dump geometry, stability analyses, construction method and performance. Since the dumps have been inactive for over 20 years, performance was assessed based on monitoring data from the past decade.

With the current knowledge and available information, three of the dumps (Grota -1, Grota 0 and Grota 1) fell into Class III (moderate hazard), while two dumps (Grota 2 and Grota 3) fell into Class IV (high hazard) with slightly lower WSRHC scores, as shown in Table 7 and Figure 5.

Grota 3's lowest score is mainly attributed to construction method (initially descending and then ascending), geometry (200 m height, 4.2×10^7 m^3 volume and overall slope angle of 27˚), foundation conditions (average overall slope angle of 25˚, overburden thickness > 5 m and type of bedrock - altered phyllite) and a high groundwater table, all affecting stability analyses.

Some key factors affecting Grota 2's score are performance (occasional small shallow failures during the rainy season, in addition to some minor deformation near the toe of the dump) and also a high groundwater table, influenced by the pit lake level, leading to local uncontrolled seepage at the lower portion and controlling overall stability.

The 'design confidence' level of the waste dumps was evaluated based on several criteria including the availability of design documents, results from field investigations and laboratory tests, the reliability and validation of engineering geological models and material parameters, understanding of predominant failure mechanisms, stability and runout analyses, construction and performance history, closure planning and post-mining land use definition, and stakeholders' expectations.

Potential failure consequences were rated based on the results of runout analyses alongside an assessment of existing facilities and downstream areas likely to be impacted by a global failure of the dumps, as listed previously in Table 1.

Table 7 Waste dumps hazard classification

Waste dump			Grota -1	Grota 0	Grota 1	Grota 2	Grota 3
Engineering geology index (EGI)	Regional setting	Description	Adverse	Adverse	Adverse	Adverse	Adverse
		Rating	3.0	3.0	3.0	3.0	3.0
	Foundation conditions	Description	Poor	Poor	Poor	Very Poor	Very Poor
		Rating	8.3	8.5	0.75	0.0	-1.75
	Material quality	Description	Fair	Poor	Poor	Fair	Fair
		Rating	10.0	8.5	6.0	10.5	10.5
Engineering geology index (EGI)			21.3	20.0	9.8	13.5	11.8
Design and performance index (DPI)	Geometry and mass	Description	Medium	Small	Medium	Medium	Medium
		Rating	6.0	7.8	6.5	6.7	5.7
	Stability analysis	Description	Very Low	Low	High	Low	Low
		Rating	1.0	4.5	8.0	4.5	3.5
	Construction	Description	Favourable	Favourable	Very favourable	Very favourable	Favourable
		Rating	11.0	13.0	15.0	15.0	11.0
	Performance	Description	Good	Good	Good	Fair	Good
		Rating	7.5	7.5	7.5	0	7.5
Design and performance index (DPI)			25.5	32.8	37.0	26.2	27.7
Waste dump stability rating (WSR)			46.8	52.8	46.8	39.7	39.4
Instability hazard			Moderate hazard	Moderate hazard	Moderate hazard	High hazard	High hazard

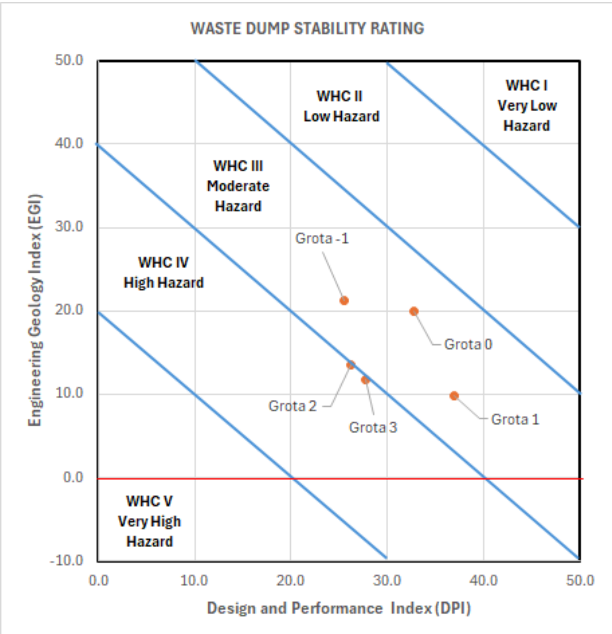


Figure 5 Waste dumps stability and hazard chart

According to the WSRHC system, Grota -1 and Grota 0 were classified as 'moderate hazard' (3). Despite the current FoS below 1.3, both dumps have good geotechnical performance, with no history of deformations over the last decade and very rare shallow failures and some small gully erosion along the berms during the rainy season. Groundwater table is at great depth and doesn't affect stability.

Design confidence level was considered 'moderate' (3), while the consequences of a possible global failure of both dumps were classified as 'high' (4) for environmental reasons, due to the existing 'RPPN Mata do Jambreiro' downstream, in addition to the top of the facilities being crossed by an old operational road, which could also pose a risk to traffic and people's lives. Thus, the R^3 score calculated for the current configuration of Grota -1 and Grota 0 (36) is classified as 'moderate' ($20 \le R^3 < 40$) according to Hawley et al. (2024) and 'high' ($30 \le R^3 < 60$) according to de Graaf et al. (2025).

The R^3 index calculated for Grota 1 was also 36, which indicates a moderate risk level ($20 \le R^3 < 40$) according to Hawley et al. (2024) and a high level ($30 \le R^3 < 60$) following de Graaf et al. (2025). With the highest FoS, the dump was classified as 'moderate hazard' (3) and the confidence level in the available data was also considered 'moderate' (3). The consequences of a possible failure were assessed as 'high' (4), since the dump is crossed by the mine's main operational road that will likely be used in the future after closure, posing a possible risk to traffic and people's lives.

Grota 2 fell into the 'high hazard' Class (4) and has a confidence level also considered 'moderate' (3). Since the dump is located upstream two sediment containment dams, the consequence of a global rupture was assessed as 'very high' (5). Thus, the R^3 index calculated was 60 and considered 'very high' by both Hawley et al. (2024) and de Graaf et al. (2025) ($60 \le R^3 < 80$).

It should be noted that the integrated mine closure plan includes the de-characterisation/removal of the two existing dams downstream of Grota 2, which would possibly reduce the impacts caused by its failure, since the frequent occupation of the area by people is not foreseen, causing a reduction in the R^3 index.

The R^3 index calculated for Grota 3 (50) was classified as 'high' by both Hawley et al. (2024) and de Graaf et al. (2025), mainly due to the existence of a sediment containment dam at its footprint, increasing the consequence of a failure to 'very high' (5). The level of confidence in the dump's design information can be considered 'high' (2.5) due to a recent geotechnical investigation program and updating of the engineering geological model. The de-characterisation of the downstream dam is foreseen in the integrated mine closure plan, which would allow a review of the consequences and the R^3 index of Grota 3.

The calculation of the R^3 scores for the waste dumps at Águas Claras mine is shown in Table 8.

Table 8 Residual risk rating (R^3) score for the waste dumps at Águas Claras mine (after Hawley et al. 2024 and de Graaf et al. 2025)

Waste dump	Existing condition ranking					R^3 score	R^3 level (Hawley et al. 2024)	R^3 level (de Graaf et al. 2025)
	Slope condition class			Design confidence rating	Failure consequence rating			
	SCC	WHC	Rating					
Grota -1	III	III	3	3	4	36	Moderate	High
Grota 0	III	III	3	3	4	36	Moderate	High
Grota 1	III	III	3	3	4	36	Moderate	High
Grota 2	IV	IV	4	3	5	60	Very high	Very high
Grota 3	IV	IV	4	2.5	5	50	High	High

5.2 Target stability reliability versus Brazilian regulations

Based on the values of FoS presented previously in Table 1, despite the integration with the environment and the good performance history of the dumps over the last decade, only Grota 1 would currently meet the requirements of NBR 13029/2024 regarding overall stability, while the other dumps have a FoS below 1.5 (2D analyses).

Grota 1’s good ranking is mainly attributed to efficient surface drainage, wide benches (>15 m), moderate overall slope angle (~25°) and the presence of large rock blocks covering the lower slopes, all contributing to overall stability (FoS > 1.5) and good geotechnical performance.

In addition to complying with NBR 13029/2024, Grota 1’s R^3 index (36) was classified as ‘moderate’ ($20 \le R^3 < 40$) by Hawley et al. (2024), what would require a FoS higher than 1.3 for closure. However, according to de Graaf et al. (2025) the dump falls into the ‘high’ category, with a minimum FoS of 1.5 being recommended. Both criteria would have already been met without geometric changes and removal of the well-developed vegetation, nevertheless, by the new framework (de Graaf et al. 2025) more rigorous analyses and robust controls would be necessary for closure.

Also by both criteria, complementary geotechnical investigation would be recommended to improve model confidence, potentially reducing the R^3 score, as well as a better definition of post-mining land use and stakeholders’ expectations for reassessing failure consequences.

The smallest facilities on the site, Grota -1 and Grota 0, also obtained a R^3 score between 30 and 40 (36), which means that the R^3 level is considered ‘moderate’ by Hawley et al. (2024) and ‘high’ by de Graaf et al. (2025). Despite their good performance history, both dumps have FoS below 1.3, which makes further investigations essential to increase the level of confidence and validate or review the current values of FoS, seeking a possible reduction in the R^3 index.

Due to the uncertainties regarding post-mining land use and the proximity of the dumps to the ‘RPPN Mata do Jambreiro’, the consequences of a failure would hardly be reduced after closure. Geometry adjustments are necessary not only to meet the TSR suggested by Hawley et al. (2024), but also to meet de Graaf et al. (2025) and NBR 13029/2024 criteria (FS ≥ 1.5).

Since Grota -1 is not officially classified as a waste dump (NBR 13029/2024 doesn’t apply), a FoS lower than 1.5 could be defined as TSR for closure based on a risk analysis considering possible damage to human lives, infrastructure and the environment. Nonetheless, this decision should be aligned with the anticipated post-mining land use and stakeholders’ expectations.

Grota 2 obtained the highest R^3 score (60) among the dumps at Águas Claras mine, classified as ‘very high’ by both Hawley et al. (2024) and de Graaf et al. (2025). The current FoS of the dump is about 1.3 and its performance is considered to be 'Fair' due to some small instabilities and displacements in its lower portion during the rainy season.

According do Hawley et al. (2024), a TSR of 1.8 < FoS ≤ 2.0 would be recommended for closure. The adoption of a FoS higher than those established by NBR 13029/2024, which would require greater interventions and geometry adjustments, may not be feasible given the current state of recovery and integration of the dump into its surrounding environment. Ideally, the minimum possible adjustments should be made to achieve the FoS required by the Brazilian standard and actions taken to ensure the reliability and maintenance of this value in a closure scenario. On the other hand, the TSR suggested by de Graaf et al. (2025) for very high-risk dumps is FoS ≥ 1.7, which is lower but still above the values defined by NBR 13029/2024.

To increase the level of confidence, which could lead to a reduction in the R^3 score and a change in the TSR suggested for closure, new complementary investigations and geological model updates should be necessary, in addition to very rigorous analyses to enable a thorough understanding of the most probable failure mechanisms and the most critical sectors. New investigations and laboratory tests could also change the ‘hazard class’ (WHC) of the dump (Class IV – high hazard), as material properties and shear strength parameters could be reviewed and stability analyses revisited, demonstrating the iterative nature of the R^3 process.

The dump is located upstream of two sediment containment dams, so until the dams are de-characterised or removed, the consequences of a possible global failure will remain ‘very high’. After that the R^3 index may be reassessed again considering post-mining land use. However, considering the current standards, the obligation to meet a FoS ≥ 1.5 remains.

The value calculated for the R³ index of Grota 3 (50) was classified as 'high' (Hawley et al. 2024; de Graaf et al. 2025). Despite the good performance of the dump in the last decade, 2D analyses using limit equilibrium methods indicate that the most critical sector has a FoS of 1.17.

Due to its geomorphological characteristics and valley-fill geometry, which provides lateral confinement to the waste dump, more rigorous stability analyses are being carried out to verify the importance of the three-dimensional (3D) effect in its stability condition. As pointed out by Hawley & Cunning (2017), although it is possible to develop a 2D model that incorporates a combination of the worst case scenario for the dump slope geometry and the conditions of its foundation, the results may still not be adequately representative of the real FoS due to the 3D effects of lateral confinement or spatial variation of material properties in the dump or in its foundation, which has been shown to be the case for Grota 3, where the results of 3D analyses are generally up to 30% higher than those found in 2D analyses.

Although NBR 13029/2024 does not explicitly specify the type of analysis (2D or 3D), it's implied that the minimum values of FoS were established based on 2D analyses. However, regulators have increasingly shown openness to the use of 3D models, particularly in high-risk and complex cases, provided the models are well-justified and technically robust. Nevertheless, FoS values obtained from 3D analyses are not always directly accepted without complementary 2D analyses or calibration, and the matter remains a topic of discussion.

For valley-confined dumps such as Grota 3 (and possibly Grota 2), where the effect of lateral confinement is so prominent, the acceptance of 3D analyses by regulators may be key in defining closure measures. In such cases, ignoring 3D effects may lead to over-conservative solutions, resulting in greater efforts, costs and environmental impacts.

An extensive drilling and laboratory testing program was carried out in 2023 and 2024 on the dump, so the current confidence level in the geotechnical parameters and model is considered 'high'. For closure, additional investigations are recommended to solve doubts in specific sectors and to increase the confidence level, enabling the reassessment of the R³ score as well as the established TSR.

The slopes of Grota 3 are buttressed by large rock blocks, i.e. the minimum FoS for local instabilities admissible by NBR 13029/2024 is 1.3. Regarding global stability, the FoS suggested as TSR would be higher than 1.5. However, as it presents good performance and is already well integrated into the environment, ideally, geometry modifications of the dump should be kept to a minimal (also ensuring surface drainage), and the selection of FoS should be evaluated through a trade-off study, considering technical, financial and environmental feasibility.

The waste dump is also located upstream from a sediment containment dam, making it impossible to reassess the impact of a potential failure until the dam is de-characterised or removed and the post-mining land use defined.

While the updated framework proposed by de Graaf et al. (2025) shows better alignment with Brazilian regulatory standards, it adopts a slightly more conservative stance compared to the original proposal by Hawley et al. (2024), notably by reducing the lower threshold for high-risk classification. As a result, waste dumps previously classified as moderate-risk are now classified as high-risk, requiring higher FoS, more rigorous analyses and robust controls. For the waste dumps at Águas Claras mine, the updated framework lost some of its sensitivity, grouping dumps of different hazard class (WHC) and varying levels of failure consequences into the same risk category.

6 Conclusion

Defining a fixed minimum FoS threshold as DAC for closure, although complying with typical Brazilian regulatory requirements, oversimplifies the complex and variable nature of geotechnical conditions, and may neglect long-term stability challenges, resulting in insufficient risk mitigation. A risk-based approach that incorporates site-specific factors offers a more realistic and defensible basis for decision-making, aligning better with sustainable closure principles and long-term safety objectives.

The use of the 'residual risk classification' index (R^3), proposed by Hawley et al. (2024) and revised by de Graaf et al. (2025) through the updating of the RSG methodology (Carter et al. 2022) and incorporating the concept of TSR for waste dumps, proved to be an effective tool for defining criteria for closure and measures to ensure long-term physical stability of the waste dumps at Águas Claras mine.

While the updated framework proposed by de Graaf et al. (2025) shows better alignment with Brazilian regulatory standards, it adopts a slightly more conservative stance compared to the original model presented by Hawley et al. (2024), notably by reducing the lower threshold for high-risk classification. As a result, waste dumps previously classified as moderate-risk are now classified as high-risk, requiring higher FoS, in addition to more rigorous analyses and robust controls. For the waste dumps at Águas Claras mine, the updated framework lost some of its sensitivity, grouping dumps of different hazard class (WHC) and different levels of failure consequences into the same risk category.

Selecting values of FoS above those required by NBR 13029/2024, demanding greater interventions and geometry adjustments, should be evaluated in light of technical, economic and environmental feasibility, given the advanced stage of recovery and integration of the dumps into the environment. Ideally, modifications should be kept to a minimal to meet the criteria required by current Brazilian standards (FoS ≥ 1.5), with efforts focused on increasing confidence levels and maintaining stability in the long-term closure scenario.

An increase in the level of confidence in the available data and input parameters, and the reassessment of the impacts caused by a possible failure after the removal of assets downstream of the waste dumps, as well as the definition of post-mining land use, could allow a reduction in the R^3 score initially calculated and, consequently, a redefinition of the TSR suggested for closure, aligned with the stakeholders' expectations.

The results also demonstrate the importance of defining the TSR for closure, as well as post-mining land use, while still in the operational phase, enabling the use of possible available resources for any geometry adjustments that may be necessary to ensure long-term stability, reducing costs and avoiding issues related to environmental and third part organisations after the deactivation of the waste dumps.

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