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# Design aspects that may be considered for the decharacterisation of mining geotechnical structures with a focus on hazardous tailings dams

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## Abstract

*After the failure events that occurred in the Brazilian mining sector between 2014 and 2022, the existing legislation was revised and new regulations were published, most notably after 2019. The prohibition of the upstream raising of dams is noteworthy as well as the establishment of deadlines for the decharacterisation of structures raised by this method. From the perspective of the decharacterisation designs, according to the regulations of Agência Nacional de Mineração (ANM), the Brazilian national mining agency, four main stages of execution must be addressed, aiming to guarantee the long-term physical, chemical and biological stabilisation of the area impacted by the construction of the dam. The final stage is the monitoring, which begins as soon as the decharacterisation works are completed and must be performed for two years or more. At least for existing hazardous tailings dams not raised by the upstream method, which are generally not removed from their construction site, the paper proposes that this stage of monitoring should be carried out in perpetuity since these dams indefinitely pose a threat to human health and the environment, and the detection of failures becomes virtually impossible after the end of any pre-established monitoring period. Risk analyses conducted concurrently with the decharacterisation designs may show that certain failure modes will eventually remain unacceptable after completion of works and monitoring, from a socioenvironmental point of view. In this sense, along with the presentation of a case study, this paper discusses that such designs should be developed under a 'risk-based' perspective and should aim at minimising the severities and probabilities of occurrence of the identified failure modes to values 'as low as reasonably practicable' (ALARP), as required by current legislation. The paper also presents brief comments and suggestions regarding decharacterisation designs of existing geotechnical structures, designs of new structures and mine closure.*

**Keywords:** *decharacterisation, perpetual monitoring, hazardous tailings dams, risk analysis, designs of geotechnical structures*

## 1 Introduction

Decharacterisation of mining geotechnical structures (tailings dams, mainly) gained even more importance in Brazil after the disasters and incidents that occurred in the Minas Gerais state in the years 2014, 2015, 2019 (Agência Nacional de Mineração [ANM] 2019) and 2022 (Parreiras 2022). With growing concerns of companies, regulatory agencies and civil society with regards to socioenvironmental impacts caused by mining activity, investment in decharacterisation works have been significantly increased. For example, the Vale company group's investment will exceed 4 billion US dollars (USD) by the year 2035 (Caramuru 2022).

Beyond having a preventive aspect to avoid new disasters, such investments were necessary due to regulatory requirements within the Brazilian mining sector; the legislation of which has undergone several modifications, most notably after 2019, to ensure greater reliability on safety management and to promote

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decharacterisation of structures with higher risks. The upstream raising of dams, for example, was prohibited throughout the country following the publication of Resolution no. 4, which also established deadlines for the preparation of technical decharacterisation designs, among other determinations (ANM 2019).

Although removal of the dam and any waste deposited in the reservoir is not mandatory, some mining companies adopted this strategy for dams raised by the upstream method as a good safety management practice, aiming to eliminate the risk of other global failures (Vale 2024). Dams that were not raised (single-stage construction), or that were raised by centreline or downstream methods, are also being decharacterised, depending on the strategic plan of the mining company.

# 2 Monitoring of decharacterised geotechnical structures

The regulatory definition of ‘decharacterisation’ of a dam[1] is relatively recent in Brazil. According to Sánchez et al. (2013), at that time it was used to designate interventions in tailings dams that had become dysfunctional due to the exhaustion of their storage capacity. Ordinance no. 70389 (ANM 2017) presented the first legal definition of ‘decharacterised mining dam’ in the country, and since then the term experienced several updates following the publication of Resolution no. 32 (Agência Nacional de Mineração [ANM] 2020), Resolution no. 95 (ANM 2022) and Resolution no. 130 (ANM 2023).

Resolution no. 95 (ANM 2022) determined that dams must undergo specific decharacterisation works, detailed in a technical design with elements that minimally meet the following four steps:

- decommissioning (ending of dam operations and removal of tailings/waste disposal equipment)
- hydrological and hydrogeological control (implementing technical solutions for minimising water input as well as reducing the water table inside the reservoir)
- long-term physical and chemical stabilisation (implementing technical solutions for minimising slope failure probability and environmental harms)
- monitoring (visual inspections, geotechnical instrumentation, radar) after completion of the previous steps.

From the constructive point of view there are three intuitive methods for the decharacterisation of a dam, whether removing the embankment or not: total, partial or no removal. Regardless of the method, hydrological and hydrogeological control, as well as long-term physical and chemical stability of the site, must be guaranteed after the decharacterisation works, in addition to the provision of adequate conditions for proper environmental reintegration (biological/environmental stability), as mentioned above.

The success of the closure project is therefore conditioned on meeting the design criteria, executing a monitoring plan and carrying out any necessary maintenance. The monitoring plan must include all activities that allow for the objectives set out in the design to be achieved, and should be developed based on the possible failure modes identified for the remaining decharacterised structure, regarding the frequency of visual inspections, and monitoring of geotechnical instrumentation, groundwater quality, radar data, etc. Nevertheless, defining a monitoring period and the criteria that allow its ending remains a great challenge for geotechnical professionals, as discussed in the following sections.

## 2.1 Post-closure care of municipal solid waste landfills: United States

The Resource Conservation and Recovery Act, or RCRA (United States of America 1976), is probably one of the first legislations that determined a period for the monitoring of decharacterised structures. The Act provided guidelines for the management of urban and industrial solid waste generated in the United States

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[1] Often, the term ‘closure’ (of a dam) is used in place of ‘decharacterisation’. The authors believe that there is an important difference between the scope of each term but, in this paper, they were used synonymously.

and defined a 30-year period for the monitoring of closed municipal solid waste (MSW) landfills, called the post-closure care (PCC) period, which was followed by entrepreneurs in general.

However, the absence of objective processes and criteria for ending the PCC generated several doubts, as described by McKenna & Dawson (1997), the Interstate Technology & Regulatory Council (ITRC 2006), Geosyntec Consultants (2006), Morris & Barlaz (2011), Ohio (2020) and the Solid Waste Association of North America (Solid Waste Association of North American [SWANA] 2021), among others, which resulted in the development of methodologies based on actual field performance of the component systems of an MSW landfill.

The ‘Evaluation of Post-Closure Care (EPCC) Methodology’ (Geosyntec Consultants 2006), for example, determined a systematic and hierarchical evaluation of monitoring data for the four common modules of MSW landfills: leachate, landfill gas (LFG), groundwater and final cover. Basically, the methodology aims to terminate PCC when it can be demonstrated that:

- LFG production is stable or decreasing
- settlement is essentially complete
- leachate quality is stable or improving
- emissions of leachate or LFG will not unacceptably impact human health and the environment (HHE) via potential pathways in air, groundwater, surface water or the soil vadose zone (SWANA 2021).

It can be noted that the performance of MSW landfills is generally related to the biodegradation of the waste mass to a certain level, for which risks to HHE are very small due to the minimum generation of leachate and gases or minimum settlements that may still occur, so as not to damage the waste cover system. In this sense, SWANA (2021) defined that an MSW landfill is ‘functionally stable’ when the active gas and leachate control systems can be ‘turned off’ (decommissioned) and it is only necessary to properly maintain the passive systems (basically, the final cover).

Hence there is still a need to monitor and to provide perpetual maintenance of the final cover so that precipitation is prevented from entering the landfill, as this could reinitiate (or increase) leachate and/or LFG generation. Performance can only be evaluated with monitoring.

## 2.2 Monitoring of mining structures

The assessment of the monitoring period within the mining sector is usually carried out in a more comprehensive manner, considering closure aspects of the whole mine and its numerous facilities, in addition to existing geotechnical structures. Basically, mining agencies and governments also make use of performance methodologies to define the monitoring period for closed mines (Stevens 2023).

In Brazil, Resolution no. 68 (ANM 2021) determines the preparation of a document that comprises the mine closure plan (PFM). Although the PFM demands actions that allow for the relinquishment of the mining operational title, it does not stipulate any post-closure monitoring period. For the monitoring of decharacterised mining dams, two years is the minimum regulatory period, as defined by Resolution no. 95 (ANM 2022) and Resolution no. 130 (ANM 2023). This period appears to be too short, given the need to guarantee conditions for the long-term physical and chemical stability of the structure and the impacted area, and to follow the development of vegetation aimed at achieving biological/environmental equilibrium.

Depending on the closure concept, failures may still have harmful impacts on HHE. For remaining structures that store hazardous waste, for example, it seems clear that certain risks may become unacceptable after only two years of monitoring, despite compliance with legislation. A slope failure on a dyke that stores hazardous saturated tailings, three years after its closure, that eventually exposes the waste, or possible groundwater contamination caused by problems in liner systems, are two possible scenarios to illustrate that the assessment of the monitoring period should be at least based on specific criteria considering the probable remaining risks in the long-term.

It may not be reasonable to assume that there will be no anomalous events after the end of the monitoring period, even if it is long, since the probabilities of occurrence of certain failure modes may be reduced or minimised but not eliminated, considering remaining structures. In the long term, doubts about their performance may arise, especially after several cycles of weathering (or extreme weather events) and the re-establishment of local flora and fauna that may also cause damage to the system (e.g. the polymer of geomembranes can oxidise/degrade, and the roots of bushes and trees can damage liner systems, as mentioned by Safari et al. 2011 and SWANA 2021, respectively).

Within this context, current international practices are moving towards the implementation of perpetual monitoring of decharacterised structures (Kuyek 2011; Raffensperger et al. 2011; SWANA 2021), with inspections and maintenance carried out on a regular (typically annually) basis. Should there be an event that may affect the structure (seismic load, severe weather, etc.), a special inspection is recommended as well. If a failure occurs, the severity of the event must be evaluated for the determination of the intervention needed, and the responsibilities and costs associated with it should be clearly defined between the mining company and the government/mining agency, depending on whether the mine is still operational or not.

In summary, designs should ensure the minimisation of risks associated with the structure that is being conceived or decharacterised, i.e. they should be developed on a ‘risk-based’ perspective, as mentioned above and as discussed below in more detail.

# 3 Risk evaluation on decharacterisation designs

The strategic objectives of any organisation are influenced by internal and external uncertainties. The effect of such uncertainties on the objectives is called ‘risk’, often quantified as a ‘likelihood x consequence’ calculation. To control the possible effects of risks associated with these uncertainties, organisations manage, analyse and make decisions that allow them to identify whether risks can be minimised (Associação Brasileira de Normas Técnicas [ABNT] 2018).

In the mining sector, according to the International Council on Mining and Metals (ICMM 2008), risk assessment must be carried out from the early onset of a mine master plan so that possible unexpected events can be readily handled, with the necessary financial provisions already planned. The sooner the risks and unknowns are reduced, the greater the potential for achieving specific objectives. In the same way, the International Commission on Large Dams (ICOLD 2022) indicates that a risk management plan should be prepared at the planning phase of a tailings storage facility (TSF), to identify the potential risks, and be updated regularly as the project progresses through the TSF life phases.

At the mine closure stage, the greatest physical risk appears to be associated with erosion caused by surface runoff, as described by McKenna & Dawson (1997), who evaluated 57 abandoned mines in Canada and the United States to investigate mine closure practices. In the long term, uncorrected erosion progressively increased, eventually resulting in local instability. Accordingly, based on the ‘progressive closure’ concept for mines defined by the Asia-Pacific Economic Cooperation (APEC 2018), Januário & Mendanha (2020) discuss the importance of developing a closure plan even before the operation of the mine, and integrating it with other enterprise processes for a progressive reduction of costs, risks and long-term liabilities.

In Brazil, the implementation of the Risk Management Process for Mining Dams (PGRBM) was determined by Resolution no. 95 (ANM 2022). Despite mentioning the need for the PGRBM to precede each phase of the lifecycle of a dam, it does not explicitly mention the need for preparing risk analyses for decharacterisation designs. In this way the reduction of risks to values ‘as low as reasonably practicable’ (ALARP), as defined by the Canadian Dam Association (CDA 2013), should be considered in such designs — using failure modes and effects analysis (FMEA), hazard identification and risk assessment (HIRA) or other proper methodology.

# 4 Case study

This case study presents the decharacterisation design of a hazardous tailings dam built as a perimetral dyke in a mine located in Brazil, and the risk analysis of the design with technical solutions that the geotechnical practitioner could implement for the reduction of the highest risks determined.

## 4.1 Executive design and former decharacterisation design of the tailings dyke

The dyke design previewed the execution of a perimetral embankment in compacted sandy-silty soil and a liner system composed of a compacted clayey soil layer (CCL) of about 50 cm in height over the foundation, superimposed by a 1.5 mm-thick high-density polyethylene (HDPE) geomembrane.

Under the CCL, the design specified the execution of an internal drainage system (‘witness drain’) to collect possible downward flows from the tailings that could indicate failure within the liner system (the water table is deep in the region and for that reason no upward flow was expected into this drain). Another internal drainage system (a blind drain) would be used to pump the water present in the saturated tailings to accelerate consolidation. The blind drain, however, was not built.

At the end of the operation of the dyke, for closure purposes, tailings should be covered by a geotextile blanket topped by a 50 cm layer of CCL, a 1.5 mm-thick HDPE geomembrane and another layer of CCL, with sufficient volume to meet the final required slope (1.5%) and a maximum thickness of the cover system on its central part of 2 m, thus isolating the contaminated material (Figure 1).

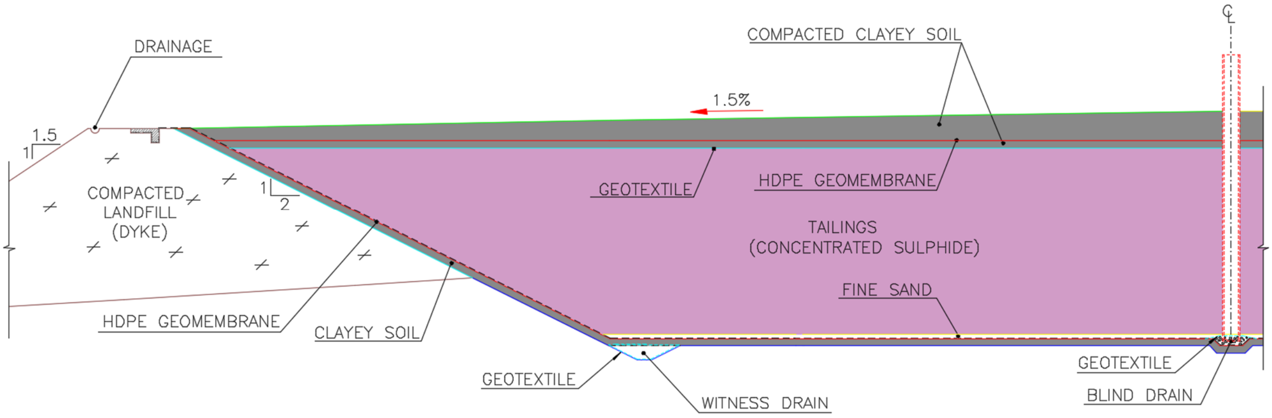

**Figure 1** **Typical cross-section of the decharacterisation design of the hazardous tailings dyke**

## 4.2 Concept of the new decharacterisation design

The cover system was not executed as specified in the detailed design as there was precipitation of salts on the surface of the cover soil due to the oxidation of the sulphide present in the tailings. During a technical visit in 2022 it was observed that neither the top HDPE geomembrane nor the CCL had been implemented; only a 2 m-thick layer of a silty material called ‘trafficability layer’, widely used in the mine, had been applied.

Therefore, another decharacterisation design was developed. It proposed the execution of a new cover system to prevent upward flows (from the tailings to the surface) and downward flows (rain infiltration) by means of a capillary barrier between the existing cover (‘contaminated’ soil) and the new cover, to be constructed with ‘trafficability’ soil and to function as a store-and-release layer (Figure 2).

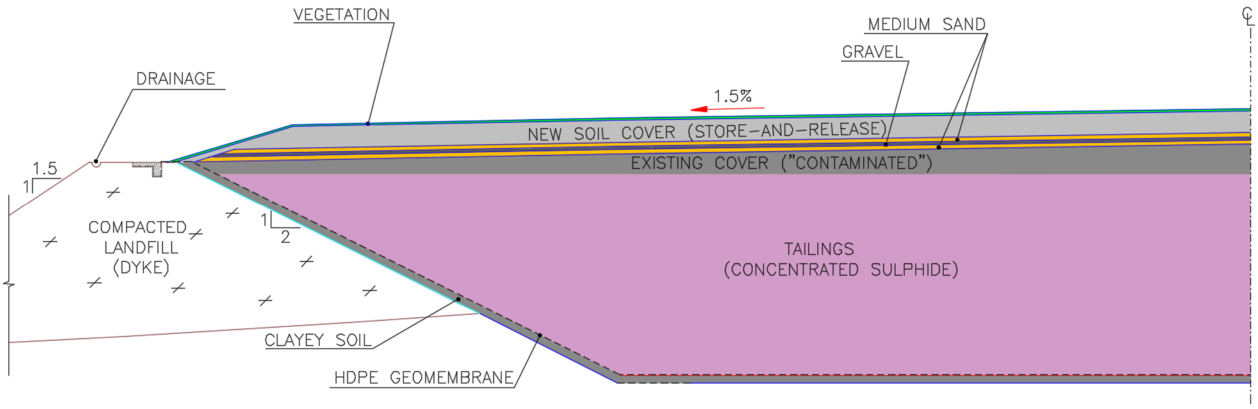

**Figure 2 Typical cross-section of the new proposed decharacterisation design**

Cone penetration tests indicated the existence of remaining excess pore pressures ($u_e$) in the tailings, so geodrains were proposed for $u_e$ dissipation. In addition, laboratory characterisation and shear resistance tests of the embankment materials and the existing cover soil made it possible for the preparation of stability analyses of the embankments, built at an inclination of 1.5H:1.0V (external slope).

Although the safety factors found were considered satisfactory (due to a very competent foundation), doubts regarding the long-term stability of the structure remained, based on the observation of erosion processes on the slopes. A risk analysis of the decharacterisation design was then prepared.

## 4.3 Risk analysis of the decharacterisation design

A risk analysis is a systematised process that aims to measure, qualitatively and/or quantitatively, the possible impacts arising from a potential risk event so that preventive measures can be taken to minimise potential damage. Among the methodologies commonly used, FMEA and HIRA stand out in geotechnical mining practice in Brazil.

Using FMEA methodology, possible failure modes are determined and each of them is associated with values assumed for severity (S), probability of occurrence (O) and probability of detection[2] (D). The multiplication of the three factors results in a risk priority number (RPN) of the identified failure mode that must be evaluated regarding its acceptability and mitigation priority, if necessary.

For the new decharacterisation design of the tailings dyke a qualitative FMEA was prepared to evaluate the remaining risks. First the analysis identified the system (dyke or dam) and its function (storage of hazardous waste). Next the system was subdivided into subsystems (embankment, foundation, internal drainage, liner system and new cover) and their potential failure modes were listed (Table 1).

For each failure mode the S were identified in four distinct categories (environmental, legal, health and community) on an effect scale that varied between 1 (very low) and 10 (catastrophic). After that, all potential causes were determined. For each cause, the O of the event ranged between 1 (unlikely) and 10 (very likely). Again, for each cause, control measures that aim to reduce the probability of occurrence, or that allow the failure to be detected before its harmful consequences occur, were also identified.

Finally, for each control, the D was determined to verify whether the failure could be detected after it has occurred but before causing any damage to HHE. A scale of 1 to 10 was used, where 1 means that the control is almost certain to detect the problem and 10 means that the control is almost certain not to detect the problem (or there is no available control measure).

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[2] In this paper, detection (D) was considered as the probability of detecting failures and acting on prevention before they could cause any damage to HHE; thus differently from the concept adopted by Espósito & Palmier (2013).

**Table 1 Definition of the subsystems and their possible failure modes**

| Subsystem | Failure mode |
|---|---|
| Embankment | Erosion on slopes or slope failures with tailings mobilisation |
| Embankment | Erosion on slopes or slope failures without tailings mobilisation |
| Foundation | Embankment slide due to foundation failure |
| Internal drainage (witness drain) | Damaging under pressure to the witness drain |
| Liner system | Percolation through the lower portion of the geomembrane (bottom of the reservoir) with contamination of the water table |
| Liner system | Water emerging from the embankment (coming from the reservoir) due to liner failure |
| New cover | Accumulation of water on the surface, with consequent inefficiency of the new cover system and precipitation of salts |

By multiplying the values admitted for the parameters S, O and D, the RPNs were calculated for each failure mode. Values greater than 100 were considered unsatisfactory. Two critical failure modes (RPN > 100) were identified, and solutions for their mitigation were proposed to the mining company as follows:

- erosion on slopes or slope failures without tailings mobilisation
  - RPN obtained was equal to 160 (S = 8, O = 10, D = 2)
  - solution proposed the use of proper geosynthetics and vegetation for erosion control
- percolation through the lower portion of the geomembrane (bottom of the reservoir) with contamination of the water table
  - RPN obtained was equal to 150 (S = 10, O = 3, D = 5)
  - solution proposed performing perpetual groundwater monitoring by means of water monitoring wells.

## 4.4 Risks after the end of the monitoring period

Despite the subjectivity in choosing numbers for S, O and D, the above risk analysis was developed considering regular inspections which allow for the identification of failures. Nevertheless, once monitoring is finished (whenever it happens) no failure can be identified, so the D number must be changed to its maximum value for each failure mode (10, in this case).

Thus the RPNs associated with other failure modes for the study case presented herein (e.g. slope instability, capillary barrier malfunction, etc.) became unacceptable too, so additional measures were proposed that consider the reduction of S and O (e.g. to reduce the angle of the external slopes of the embankment, and to perform field experiments with different layouts for the evaluation of an optimised soil cover, including the capillary barrier).

Furthermore, for the reduction of D, perpetual field inspections with a minimum annual frequency (once the dyke contains hazardous tailings) were recommended. Any necessary maintenance should be carried out by the mining company while the mined area is under its responsibility.

# 5 Final comments and suggestions

In the light of the observations described in this paper, some comments and possible improvement opportunities for future designs related to mining geotechnical structures and mine closure are presented.

## 5.1 Develop technical standards for decharacterisation designs

Currently in Brazil there are no technical standards that indicate the objective criteria to be followed in decharacterisation designs of geotechnical structures. The authors understand that these normative should be developed and should be based on the need for mitigating the remaining risks of the structure intended to be closed, i.e. a risk-based perspective.

## 5.2 Use mine closure concepts in all designs

All designs should consider using various mine closure concepts, such as:

- ‘Landscape engineering’ (McKenna & Dawson 1997)

  *(‘An …) attempt to provide better direction and tools for this new approach to produce landscapes that meet clearly defined goals predictably and reliably with lower residual liability and at overall lower cost.’*

  *‘Setting goals, designing for closure, using landforms and vegetation that have sustainable and reliable long-term performance.’*

- ‘Geomorphic approach’ (Sawatsky et al. 2008)

  *Applying ‘(…) techniques for replicating natural landforms and natural drainage systems (…) to achieve similar composition, contouring, and hydrologic functions as undisturbed landforms.’*

  *‘In place of the typical geometric waste dump shapes with flat tops and homogenous benched sides, the geomorphic approach offers micro-topography provided by dendritic drainage courses with decreasing slopes at the base of the landform, mimicking mature natural landforms.’*

- ‘Design for closure’ (International Network for Acid Prevention 2014)

  *‘Design for closure requires that the full mine-lifecycle, from development to closure, be considered in the design of the mine components so that the desired mine closure conditions are achieved.*

- ‘Progressive closure’ (APEC 2018)

  *‘Mine closure activities undertaken during operation of the mine. Often used to reduce closure work needed at end of mine life when cash flow from the mine is at its lowest point. Progressive closure in parallel with mine operation may also make use of operational activities (e.g. waste handling) to achieve zero- or low-cost closure outcomes.’*

- ‘Cradle-to-cradle’ (Herrington & Tibbett 2022)

  *‘(…) the starting landscape and the agreed future post-mining landscape are of equal or greater function and value (including biodiversity and ecosystem services), where a use for all excavated material is assessed and agreed, with the concept of ‘waste’ being eliminated as all material will have a prescribed use either on or off the mine site.’*

- ‘Progressive reclamation’ (Okane Consultants 2023)

  *‘Progressive reclamation means planning with the end in mind, solving potential issues like dust management before they arise. Progressive reclamation is the best way to instil trust in stakeholders, reduce liability long-term, and maintain positive relationships with impacted communities and Indigenous rights holders.’*

> *'One of the preferred progressive reclamation strategies for dust management is revegetation.'* (…) *'Revegetation of exposed tailings materials is most successful when planned from the beginning of the mine lifecycle. This includes:*
>
> - ○ *developing successful and achievable completion criteria for revegetation*
> - ○ *examining the chemical and physical properties of the soil*
> - ○ *field trials*
> - ○ *ongoing monitoring of revegetation and cover system performance.'*

In addition, decharacterisation designs should be included in the scope of mine closure plans, which in turn should consider the elaboration of land rehabilitation plans, as required by Brazil (Brasil 1989) and described in ABNT (1999).

## 5.3 Consider long-term impacts

As mentioned by ICOLD (2013), an increasingly intense focus on long-term sustainability of projects:

> *'(…) has developed through the somewhat negative experiences of the past where developments have taken place perhaps without due consideration of the impact they may have on future generations.'*

In this sense one should consider that the good performance of decharacterised structures in the past may not necessarily imply the same performance in the future, as weathering and other dynamic processes on Earth will remain in perpetuity. In the long term (i.e. after the period of post-closure or passive care) doubts may arise. Higher uncertainties mean higher risks.

## 5.4 Perform risk analysis and minimise risks

Risk analyses of decharacterisation designs should always be developed and these designs should aim at minimising the S and O of the identified failure modes to ALARP values so that risks would become acceptable, even without monitoring for some cases (structures that contain non-hazardous waste, for example) and some failure modes (with low values for S and/or O) once D must be changed to its maximum value after the monitoring period for each failure mode identified.

## 5.5 Flatten steep slopes and cover the soil

Geotechnical risks related to mining dams and other structures are frequently associated with physical stability of the slopes. As part of the Minto mine closure project in Canada, SRK Consulting (2016) estimated soil losses on vegetated and non-vegetated slopes with different inclinations and lengths using the Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC) equation presented by Wall et al. (2002). The results obtained are presented in Table 2.

Extrapolating the values obtained by SRK Consulting (2016) using exponential regression one can verify that soil losses approach zero for vegetated slopes with inclinations in the order of 10H:1V, which in practice can be very difficult to achieve. Even so, it is appropriate that closure designs consider reducing the inclinations of the remaining slopes, i.e. final slopes should become as flat as reasonably practicable to minimise erosion and instability occurrence. Slopes of at least 3H:1V are encouraged, especially in tropical countries like Brazil (with high pluviometry).

It can also be seen that covering the soil with proper vegetation significantly reduces slope erosion (thus reducing operational costs with sump desilting, for example) and eventually avoids slope mobilisation/failure, as mentioned by Okane Consultants (2023). Hence it is recommended that vegetation should be placed as soon as the final geometry of the slope is reached for geotechnical structures.

**Table 2 Average annual soil loss for Minto mine using the Revised Universal Soil Loss Equation for Application in Canada equation (SRK Consulting 2016)**

| **Slope condition** | | **Average annual soil loss (T/ha/yr)** | | | |
|---|---|---|---|---|---|
| | | 50 m | 85 m | 100 m | 150 m |
| **Non-vegetated** | 2.5H:1V | 31.8 | 41.8 | 45.6 | 56.2 |
| | 3H:1V | 26.2 | 34.1 | 37.1 | 45.5 |
| | 3.5H:1V | 22.1 | 28.6 | 31.0 | 37.8 |
| | 4H:1V | 19.0 | 24.3 | 26.4 | 31.9 |
| | 5H:1V | 14.6 | 18.4 | 19.8 | 23.7 |
| **Vegetated (80% short-rooted plant coverage)** | 2.5H:1V | 3.7 | 4.8 | 2.3 | 6.5 |
| | 3H:1V | 3.0 | 3.9 | 4.3 | 5.2 |
| | 3.5H:1V | 2.6 | 3.3 | 3.6 | 4.4 |
| | 4H:1V | 2.2 | 2.8 | 3.0 | 3.7 |
| | 5H:1V | 1.7 | 2.1 | 2.3 | 2.7 |

## 5.6 Implement perpetual monitoring

It is only possible to say that a geotechnical structure is safe if: (1) it is properly characterised, (2) there is a known history of the depositional environment and (3) if it is being monitored. For sites with 'poisons that will last longer than the safeguards', Kuyek (2011) mentions that even perpetual care is not good enough.

For decharacterised structures that contain hazardous waste, perpetual monitoring of groundwater and slope conditions should be implemented as a minimum precaution, with inspections and maintenance carried out on a regular basis (typically annually) and after every event that may affect the integrity of the structure (seismic load, severe weather, etc.). Visual inspections using drones as well as automated instrumentation and satellites/radars like InSAR, with reports being generated at predetermined intervals, may reduce monitoring costs.

Furthermore, the authors believe that Principle 7 of the Global Industry Standard on Tailings Management (ICMM 2020) should also address the post-closure phase for monitoring systems, as Principles 4, 5 and 6 already consider.

## 5.7 Choose an appropriate location and geometry for new structures

To minimise impacts on the closure phase, structures that are intended to store hazardous waste should be constructed in locations that minimise future decharacterisation costs and risks, including those associated with possible changes in environmental policies/legislation and the unplanned growth of communities, as noted by Januário & Mendanha (2020). Likewise, new structures should also be designed with geometries favourable to the required long-term physical stability. To minimise erosion and instability concerns, designs considering flat slopes (as flat as reasonably practicable) are encouraged, as mentioned above.

## 5.8 Prioritise community needs in future land use

Finally, with the aim of making a positive impact on HHE, the authors suggest that mining companies should prioritise the needs of local communities when planning the future use of mined areas. More than simply revegetating these areas and using them for ecotourism or other leisure-related activities, there may be a great opportunity to produce abundant food (and/or sustainable energy) for the benefit of local families.

Instead of transforming these areas into 'new forests' they may be transformed into agroforestry. Examples of such uses can be found in McKenna (2018) and Yu et al. (2023).

# 6 Conclusion

This paper presented some relevant aspects for the decharacterisation of geotechnical structures, based on general concepts and requirements of the main Brazilian regulations applied to mining, which have been updated after the failure events that occurred in the country between 2014 and 2022.

Among the decharacterisation stages required by Resolution no. 95 (ANM 2022), defining a monitoring period is a big challenge for geotechnical practitioners. The minimum regulatory period of two years appears to be too short, given the need to guarantee long-term physical, chemical and biological/environmental stability. For that reason, designs should be based on the possible remaining risks after closure, evaluated by means of risk analysis developed with methodologies like FMEA and HIRA.

As shown by the study case presented herein, risks associated with diverse failure modes can become potentially harmful if monitoring is not being carried out. Therefore, performing perpetual monitoring of geotechnical structures containing hazardous waste (dams, in general) is mandatory in the authors' opinion, since no failure can be detected without monitoring and the risks associated with these structures may even increase over time due to the Earth's dynamic processes, which will remain forever.

More than evaluating risks, designs should consider minimising the severities and probabilities of occurrence of as many failure modes as possible. For that purpose, the use of diverse mine closure concepts can be of great significance. Furthermore, conservative geometries (as flat as reasonably practicable) may be adopted.

Finally, on the social aspect, the implementation of agroforestry systems or the use of mined areas to generate sustainable energy can become important contributions to local communities, more than simply revegetating degraded areas.

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