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Preliminary framework for filtered tailings deposition design considerations: a South African perspective

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Abstract

As global mining operations increasingly adopt filtered stack tailings (FST) deposition technology, the need for a design consideration framework becomes evident. To an extent this gap was filled in March 2024 when the BHP Rio Tinto Tailings Management Consortium's recommended approach to filtered tailings system design was published. For a South African context this gap still prevails as limited literature has been published on this topic and the implementation of the FST technology is still immature. The proposed framework is therefore aligned to South Africa's unique environmental, regulatory, and geotechnical conditions. The framework addresses key challenges in FST implementation, including material characterisation, site-specific conditions, technology selection (filtration, transportation and stacking), as well as environmental and regulatory considerations. Filtered tailings offer a sustainable alternative to conventional wet tailings storage facilities by enhancing water recovery and reducing environmental risks. However, large-scale adoption in South Africa remains limited due to high capital costs, technical barriers, and a lack of standardised methodologies. This preliminary framework aims to bridge these gaps by aligning global best practices with local parameters to guide tailings design engineers in evaluating and implementing FST systems. The framework aims to facilitate informed decision-making through design consideration guidelines, promoting environmentally sound and structurally robust tailings management practices. By supporting trade-off analyses between different deposition methodologies, this research advances sustainable mining practices in South Africa while contributing to the global discourse on tailings management innovation.

Keywords: *filtered stacked tailings, dry stack, framework, material characteristics, design evaluation*

1 Introduction

Tailings management remains one of the most critical challenges facing the global mining industry due to its environmental, economic, and safety implications. High-profile tailings storage facility (TSF) failures, such as the Fundão collapse in 2015 and the Brumadinho disaster in 2019, have highlighted the catastrophic consequences of conventional wet tailings storage methods, including significant loss of life, extensive environmental degradation, and economic penalties (Cacciuttolo & Atencio 2023). In response, the Global Industry Standard on Tailings Management (GISTM) was launched in 2020 by organisations such as the International Council on Mining and Metals, United Nations Environment Programme, and Principles for Responsible Investment. According to Global Tailings Review (2020) the GISTM advocates a zero-harm approach, emphasising no human fatalities and prioritising environmental protection throughout the life cycle of TSFs.

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Among the innovative approaches promoted by the GISTM is the recommended use of filtered stack tailings (FST), a technology that mechanically dewaters tailings to produce a stackable 'dry' material. This method eliminates the need for large water-retaining dams, thereby significantly reducing risks associated with structural instability and water management. FST has been successfully implemented in several mining regions worldwide, including Alaska, Australia, Peru, Chile, Namibia, and Turkey. Its water-saving capabilities and enhanced stability make it particularly effective in arid and semi-arid environments (BHP Rio Tinto 2024; Inci et al. 2023).

South Africa, with its complex mining landscape, faces unique challenges in tailings management. The country has recorded four major TSF failures since 1974 and hosts 101 high-risk tailings dams as of 2020 (Warburton et al. 2020). These incidents underscore the urgent need for improved tailings storage practices to safeguard nearby communities, protect the environment, and ensure the sustainability of mining operations. Moreover, South Africa's water scarcity, particularly acute in regions like the Northern Cape, exacerbates the limitations of conventional wet tailings storage methods, which compete with other sectors for dwindling water resources. By recovering and reusing water, FST technology offers a sustainable alternative that addresses these pressing issues (Copeland et al. 2023).

Global mining trends and funding requirements further highlight the need to adopt FST in South Africa. The introduction of the GISTM in 2020 has increased scrutiny on TSFs driving safer and more sustainable practices. Compliance with these standards is increasingly linked to funding opportunities, which in turn encourage innovation. The successful implementation of FST in arid and semi-arid countries such as Peru, Chile, Namibia, Australia, and Turkey, as well as in seismic regions, highlights its feasibility and provides valuable insights for potential adoption in South Africa.

Despite the advantages of FST, there remains a lack of clear guidance and standardised methodologies for implementing these facilities, particularly within the South African context. Most research and practices focus on conventional wet tailings storage, leaving a gap in the literature and industry standards for the evaluation and design of FST.

2 Theoretical background

Tailings management has evolved significantly, influenced by global advancements in geotechnical and environmental engineering. The FST methodology represents a pivotal shift from traditional TSF to more sustainable practices. However, the development and implementation of FST are grounded in established design philosophies that address the unique challenges of tailings management.

Based on literature, three prominent tailings design approaches provide a foundation for current standard practices in tailings management: the Klohn Crippen Berger (KCB) tailings design approach, the BHP Rio Tinto design approach, and the Systems approach. Each of these methodologies contributes distinct perspectives, collectively guiding safe, sustainable, and efficient tailings management systems.

2.1 KCB tailings design approach

With the mining industry increasingly adopting alternative tailings technologies to mitigate the risks of conventional dams, Patterson et al. (2020) proposed a framework of key factors to consider. As depicted in Figure 1, these factors provide critical guidance for developing tailings management strategies that minimise risks across all stages of the mine life cycle, from design to closure.

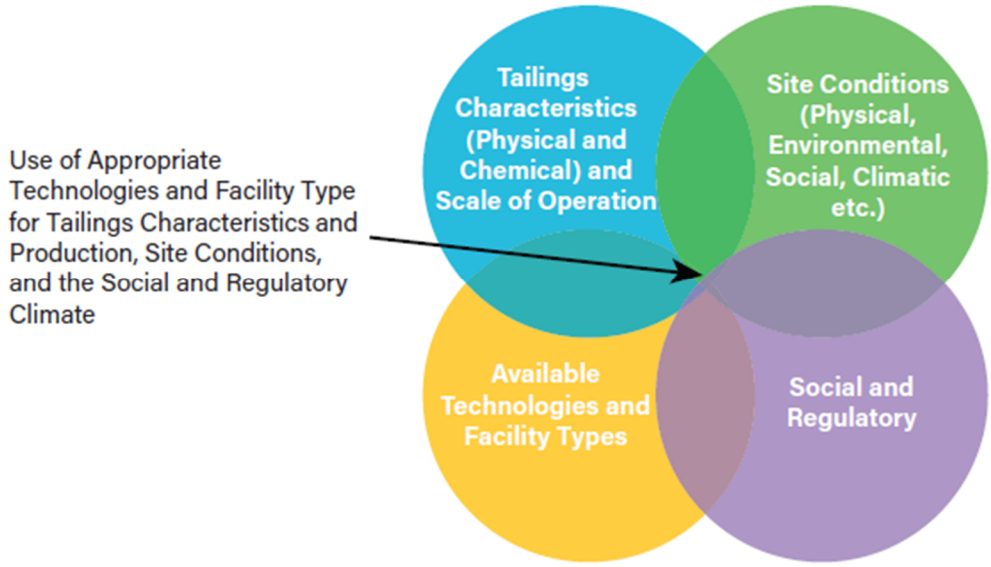

Figure 1 Key tailings management strategy (framework) considerations (figure after Patterson et al. 2020)

The proposed four main components for considerations in the tailing management framework are tailing characterisation and mine plan, site conditions, social and regulatory conditions, and lastly available technologies and facility types. It was noted by Patterson et al. (2020), that each project presents unique challenges based on site conditions, tailings characteristics, resources, and the social and regulatory environment. Selecting a management system requires evaluating the full risk profile, including life cycle costs, to align with these unique conditions. Ultimately, there is no one-size-fits-all approach to tailings management, making a holistic and adaptive strategy essential throughout the project life cycle.

2.1.1 BHP Rio Tinto design approach

BHP Rio Tinto (2024) proposed a systematic phased approach for filtered tailings management studies. This approach starts with a 'closure-first' method to ensure that the ultimate goals of stability, sustainability, and compliance with environmental and social expectations are embedded into the design and operational strategies from the outset (see Figure 2).

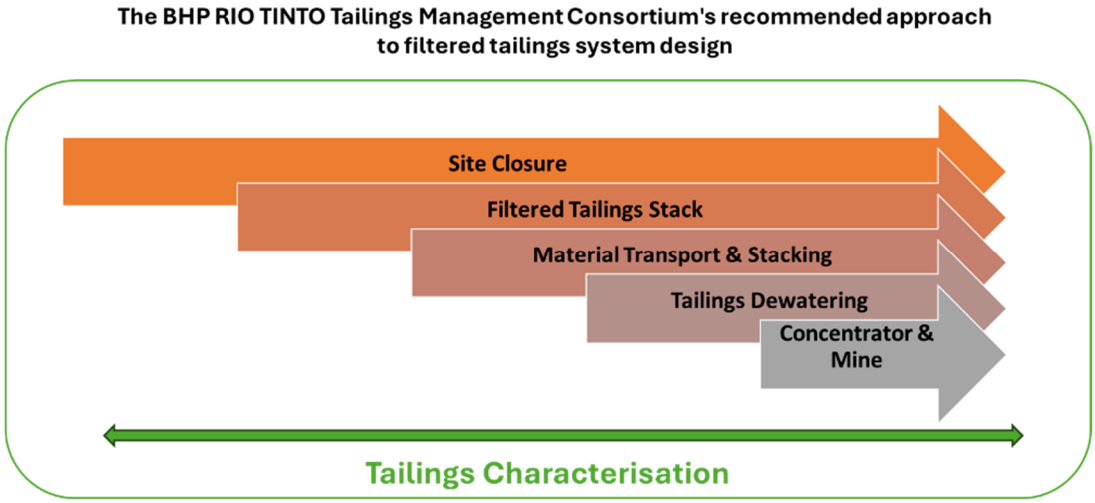

Figure 2 Approach to filtered tailings system design study, modified from BHP Rio Tinto 2024

The system design approach comprises of different components of which material characterisation is a cornerstone of the design, operation, and closure of tailings facilities. Accurate and comprehensive

characterisation provides the essential data required to ensure the safety, efficiency, compliance, and sustainability of tailings facilities throughout the project life

cycle. Material characterisation directly influences filtered tailings stack design, material transport and stacking, and tailings dewatering, as it determines the behaviour of the tailings under various conditions and informs critical decisions at each stage of the process. Physical, chemical, geochemical, geotechnical and rheology parameters are used to characterise the tailing materials (BHP Rio Tinto 2024).

2.2 Systems approach

The traditional approach to tailings management has been linear. Tailings was seen as the backend of the mining process and is widely known to be a grudge purchase. For tailings management to progress, it is required to consider the management of TSFs as part of a complex system. Küpper et al. (2020) created a tailing facility Systems approach that indicates how tailings should be integrated as part of the mine and processing plant system (see Figure 3).

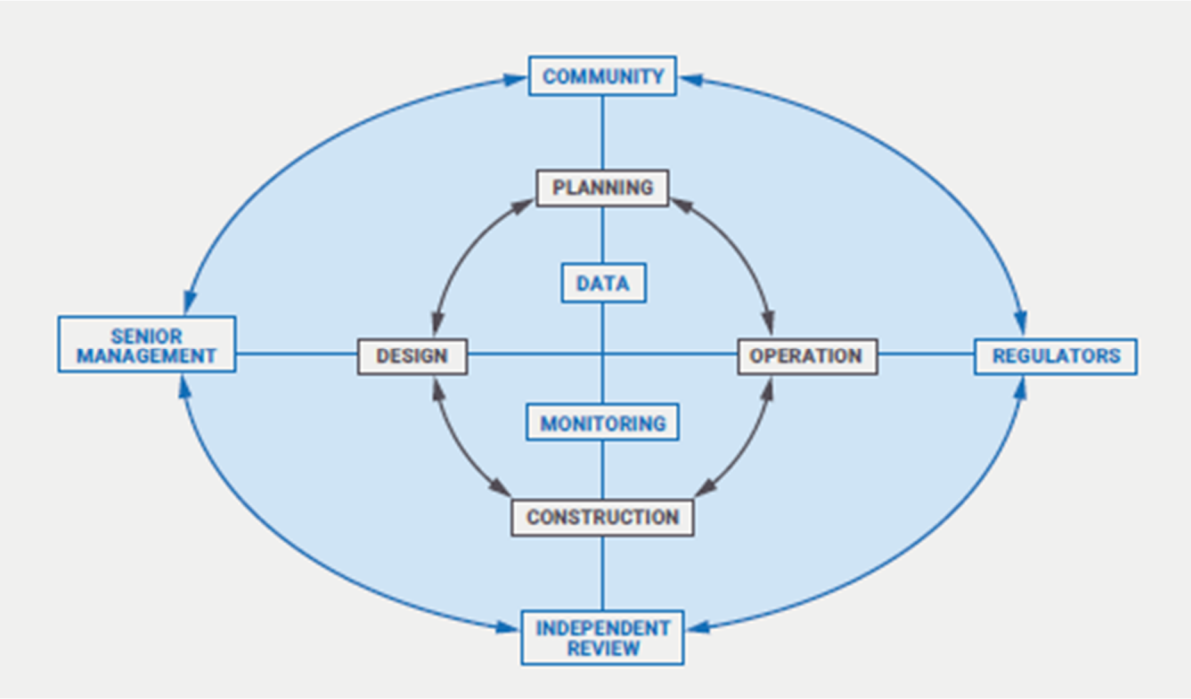

Figure 3 Elements to consider for the design of a TSF, the systems approach. Figure after Küpper et al. (2020)

When considering the tailings design, the authors highlighted four design related considerations that the Engineer of Record (EOR) should focus on, that are critical to the safety of the facility. These were get the geology 'right', get the soil mechanics 'right', get the hydrology 'right', and get the implementation 'right'. In addition to understanding the listed considerations, Küpper et al. (2020), emphasises the importance of competence and a credible review process (independent of the EOR).

2.3 Design approach overlap

There is no singular methodology for tailings design, but significant overlaps exist among the three reviewed design and management systems. Both the BHP Rio Tinto Design Approach and the Systems Approach emphasise treating TSFs as integral systems within mine design, rather than isolated components. These approaches prioritise material reviews, focusing on transportation, stacking, and dewatering technologies, which are critical in the FST context. The KCB tailings design approach similarly incorporates these elements but combines technology availability with facility type under a unified heading.

Despite differing terminologies, all three approaches identify geology, mineralogy, and tailings characterisation as fundamental considerations. The Systems approach groups material properties under 'design considerations,' while the KCB approach places significant detail under site-specific conditions. Environmental, social, and governance (ESG) compliance is another consistent theme, with varying emphasis: the BHP approach integrates it within site closure and tailings stack considerations, while the KCB and Systems approaches address it as a distinct focus area.

Although there is currently no standardised and single design approach for tailings management design considerations, there are clear themes that were reported in all three approaches. The themes were environmental/regulatory considerations, material characterisations, site-specific considerations and technology considerations (filtration, transportation and stacking).

2.4 Overview of tailings disposal in South Africa

South Africa, a global leader in mining, produces significant quantities of gold, platinum group metals (PGMs), coal, and diamonds (among other valuable minerals). Its extensive mining history has developed mature tailings management practices, yet evolving challenges call for advancements in disposal technologies and governance.

South Africa has a mature mining industry, accompanied with high standards. The upstream TSF construction method remains the country's most common tailings disposal technique, leveraging the dry climate for cost-effective drying and consolidation. Despite its mining accomplishments, the country has experienced notable tailings failures including Jagersfontein (2022), Ulundi (2021), Merriespruit (1994), and Bafokeng (1974), that resulted in fatalities as well as environmental and economic damage. While FST are not widely adopted, increasing feasibility studies for the consideration of this method in PGM and gold tailings reflect growing interest in safer alternatives and highlights the need for ongoing innovation in tailings management to address local and global challenges (Grant-Stuart 2020).

3 Methodology

The framework for evaluating FST deposition was developed through a qualitative research approach, which included:

- An extensive literature review: the study examined recent advancements in tailings management, geotechnical challenges, and global standards for FST deposition. Key sources included peer-reviewed journals, industry reports, conference proceedings, and regulatory documents, with a focus on regions with conditions similar to South Africa's, such as arid climates and seismic activity. Local trade-off studies between conventional TSFs and FST were included where possible.
- Primary data validation through expert consultations: although limited consultations with South African industry experts have already been conducted, not all aspects of the framework have been validated. Additional expert interactions will provide insights and validate this framework to ensure its relevance and adaptability to local conditions, addressing both theoretical insights and practical considerations.

The primary objective of this paper was to apply global best practices to South Africa's unique environmental, regulatory, and geotechnical requirements. The development of a structured approach enabled the preliminary framework to be both robust and adaptable, addressing the diverse, site-specific challenges encountered in a South African mining contexts.

A significant resource for this study was *Filtered Stacked Tailings: A Guide for Study Managers* by BHP Rio Tinto (2024), which provides extensive global guidelines for implementing filtered tailings facilities. This guide has been instrumental in setting a foundational standard, with this study building upon its principles to address the unique environmental and regulatory landscape in South Africa, where factors like water scarcity, seismicity, material diversity and complex terrains require localised solutions.

4 Results

A structured framework was developed to guide geotechnical trade-off studies and evaluate the feasibility, stability, and sustainability of FST facilities. The framework considers South Africa's unique environmental, regulatory, and material characteristics, highlighting the gaps in local guidelines tailored to these conditions. The proposed FST design consideration framework is presented in Figure 4 with five main components: material characterisation, site-specific considerations, technology selection (which includes filtration, transportation, and stacking), environmental and regulatory considerations and economic feasibility. This structured approach ensures a comprehensive evaluation of all critical factors for the implementation of FST systems.

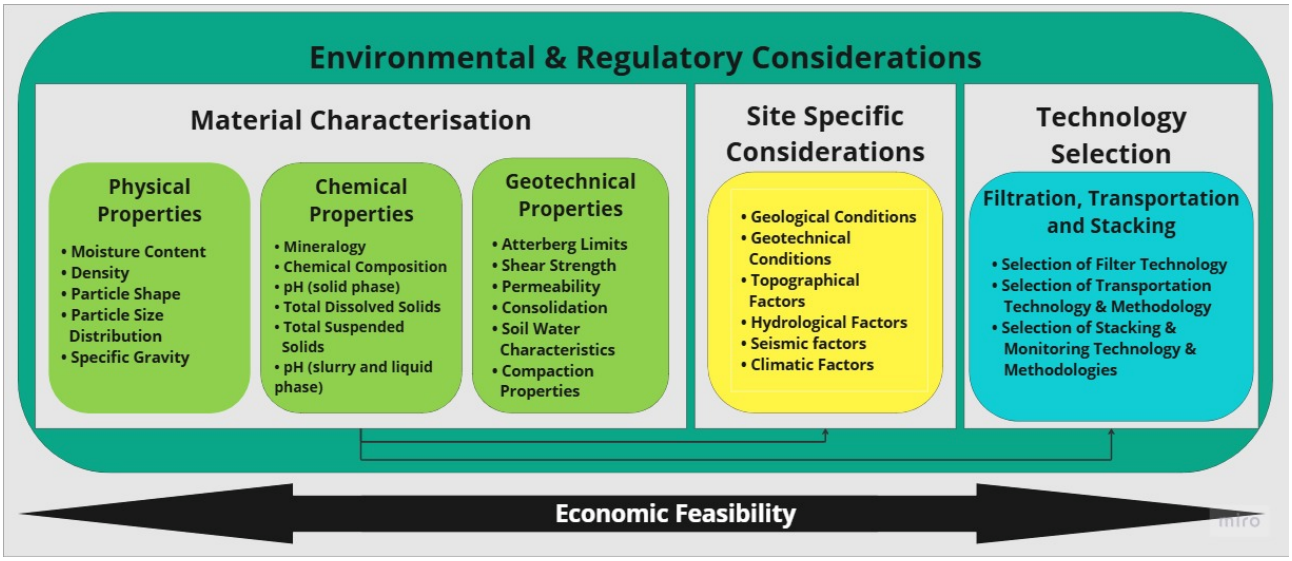

Figure 4 The proposed filtered stack tailings design consideration framework

Each component serves as a checkpoint to systematically assess site-specific conditions and requirements. This structured approach aids in identifying challenges early, reducing environmental liabilities, enhancing stability, and ensuring compliance with regulations. While this paper focuses on the South African context, the framework is versatile and can be tailored to meet the specific challenges of individual projects.

4.1 Material characterisation

The first component of the framework focuses on the physical, chemical, and geotechnical parameters of tailings material, which are critical for assessing their suitability for filter stacking and ensuring long-term stability. The key chemical and physical characterisation tests recommended by BHP Rio Tinto (2024), include the following:

- Chemical parameters focus on both solid and liquid phases and encompass tests such as atomic absorption spectroscopy, inductively coupled plasma and atomic emission/mass spectrometry, and X-ray fluorescence. These tests are vital for identifying chemical compositions, detecting potential contaminants, and supporting material assessments – such as reagent selection, occupational and environmental hazard identification, and compliance with regulatory standards. Additional parameters include conductivity, pH, total dissolved solids, and total suspended solids – which provide crucial insights into water chemistry, material handling, and equipment suitability. Zero free water measurements are also incorporated to determine the solids concentration thresholds.

- Physical parameters include mineralogical analyses using optical microscopy, X-ray diffraction, and energy-dispersive X-ray analysis to assess the composition and types of minerals – including clays and potential hazards. Particle size distribution is determined through sieves, hydrometers, and laser diffraction, while particle shape is examined using optical and scanning electron microscopes. Slurry density, moisture content, and specific gravity are evaluated using pycnometers, balances, and drying techniques. Together, these physical tests provide critical data on solid-liquid separation, rheology, consolidation behaviour, and overall storage performance of tailings, ensuring effective management and design of mining operations.

The key filter cake geotechnical characterisation tests recommended by BHP Rio Tinto (2024) include air drying tests, Atterberg limits, consolidation tests, drained and undrained settling tests, optimum Proctor dry density and moisture content, critical state line testing, direct simple shear tests, permeability tests, and soil water characteristic curve measurements. The data obtained from these tests is used to design the storage facility and define upstream processing specifications, such as the filter cake moisture target range.

Although all the listed parameters provide inputs into the material characterisation, not all parameters are equally important in every scenario. From the listed physical parameters, the most crucial are moisture content, particle shape and particle size distribution. From the listed chemical parameters, the most crucial are chemical composition (mineralogy and clay content), clay properties and feed water chemistry. From the listed geotechnical parameters, the most crucial are shear strength, permeability/hydraulic conductivity, compaction properties including optimum moisture content as well as consolidation. These critical parameters should take precedence when considering filtration, material handling, transportation, and stacking. Other properties should be evaluated on a case-by-case basis, as deemed relevant by the study manager.

4.1.1 Material characterisation: the South African context

The global and local material characterisation considerations are the same and the parameters listed by BHP Rio Tinto (2024) could therefore be applied in a South African context. One component that is currently being researched in a South African context is the presence and effects of clays.

The presence of clays and the chemical properties of feed water significantly affect tailings behaviour, especially in relation to flocculation, dewatering performance, and TSF stability. According to Vietti & van der Linde (2024), dispersive clays, which de-flocculate in suspension, often result in poor dewatering efficiency and instability in tailings storage facilities. The interplay between the physical and chemical properties of clays is particularly complex and not yet fully understood, underscoring the importance of studying these interactions in detail.

Andrew Vietti developed a classification plot for South African tailings materials highlighting the challenges associated with clays in filtered stacked tailings facilities (FSTF), especially when the fines fraction (<20 µm) exceeds 40% of the particle size distribution (PSD) (Vietti, pers. comm., 2024). This issue is exacerbated by active or swelling clays like smectite, which expand significantly when interacting with water. The methylene blue index (MBI) is an effective tool for evaluating clay activity. It was mentioned that materials like kimberlite tailings, mineral sand slimes, and bentonite are challenging to dewater due to their high fines content and the presence of active clays. These characteristics increase the likelihood of filter cloth clogging and reduce permeability, leading to lower filtration efficiency. Additionally, active clays can result in lower-density thickener underflows, which indicate poor flocculation and inadequate settling. These underflows feed into the filter at suboptimal densities, further complicating the dewatering cycle. Addressing these challenges requires a detailed understanding through analyses of clay properties, fines content, and the impact of water chemistry on their behaviour.

4.2 Site-specific considerations

Site-specific considerations are essential in the design and management of FSTFs to ensure structural stability, environmental protection, and operational efficiency. Tailoring FSTFs to geological, topographical, hydrological, climatic, and seismic factors helps address unique site risks and could minimises environmental

impacts. This approach allows for proactive risk management and supports the long-term safety and sustainability of tailings facilities.

4.2.1 Geological, hydrological and geotechnical considerations

Investigating the ground (soil and rock) conditions of a FSTF foundation is crucial for ensuring stability, safety, and compliance with environmental regulations. Geotechnical studies assess soil strength, deformation, and load-bearing capacity to confirm the foundation can handle the weight of the tailings over time. Hydrogeological assessments and seismic evaluations are also necessary and coupled with the foundation investigations. These investigations are essential for effective FSTF design and operation (Copeland et al. 2006; Davies 2011).

4.2.2 Climatic factors

The Weinert N-value, as developed in 1980, provides a valuable tool for understanding weathering dynamics by relating climatic conditions specifically, the balance between evaporation and precipitation to weathering processes. This metric is particularly relevant in regions like South Africa, where climatic variability strongly influences the geotechnical and environmental characteristics of soils and rock formations (Weinert 1980). The index is calculated as per Equation 1:

$$N = \frac{12 \times E}{P} \tag{1}$$

where:

E = evaporation for the warmest month (usually in mm, often derived from potential evapotranspiration for the warmest month)

P = mean annual precipitation (in mm).

The macro climate of South Africa N-values is illustrated in Figure 5.

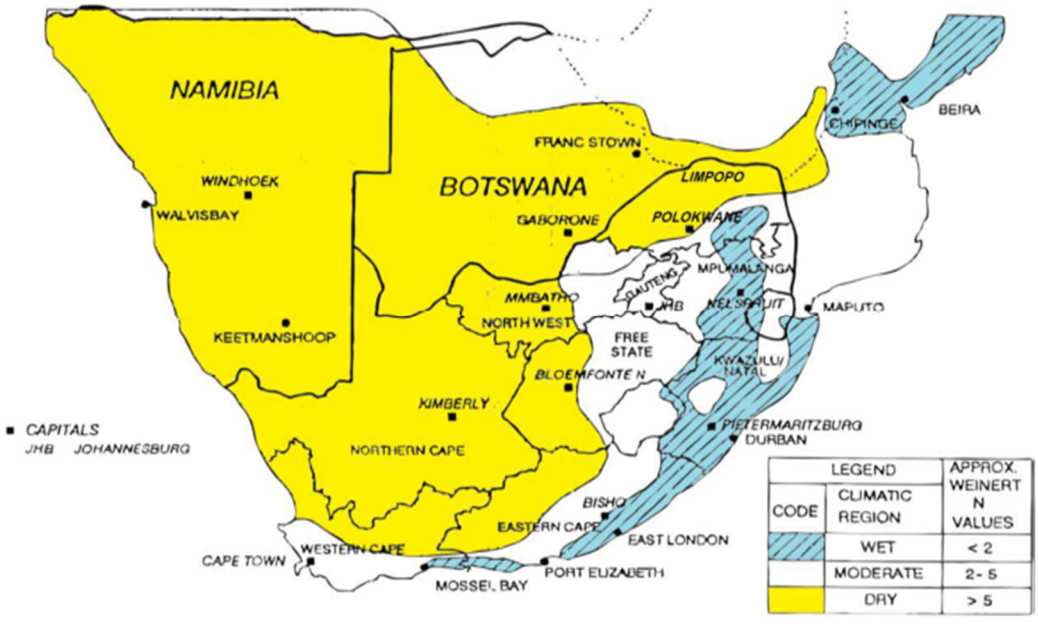

Figure 5 Macro climatic regions of Southern Africa, adapted from Weinert (1980)

The proposed index ranges for classifying regions based on aridity in South Africa are as follows: regions with N < 2 are identified as wet, regions with N between 2 and 5 are considered moderate, and regions with N > 5 are classified as dry.

Thornthwaite's moisture index (Im) is another method used to classify climatic zones in South Africa. Im is a function of evapo-transpiration, which is dependent on vegetation and rainfall. Im provides a measure of the moisture surplus (positive value) or moisture deficit (negative value). Thornthwaite's Moisture Index is calculated as per Equation 2:

$$lm = \frac{(100 \times \mathrm{s}) - (60 \times d)}{n} \quad (2)$$

where:

S = moisture surplus (amount of water available after meeting evapotranspiration demands)

D = moisture deficit (shortfall of water relative to the evapotranspiration needs)

N = total potential evapotranspiration (total water that could evaporate and transpire under ideal moisture conditions).

The classification of regions based on the Im index in South Africa is as follows:

- Im >100 is classified as very humid
- Im between 20 and 100 as humid
- Im between 0 and 20 as moist sub-humid
- Im between -20 and 0 as dry sub-humid
- Im between -40 and -20 as semi-arid
- Im <-40 as arid.

Through integrating the Im and Weinert N-Values into site assessments, engineers can account for moisture dynamics, enhancing the resilience and sustainability of geotechnical and environmental designs in South Africa's varied climatic landscape.

4.2.3 Topographical factors

Topographical conditions also influence facility design. Variations in terrain, particularly in undulating or uneven areas, complicate tailings deposition and necessitate careful planning to mitigate risks such as settlement and slope failure. Copeland & Teixeira (2019) describes the use of phased developments and engineered systems, such as conveyors and stackers, to accommodate challenging topographies. These approaches are critical for ensuring the operational stability of tailings facilities, particularly in regions with complex surface conditions.

4.2.4 Seismic factors

South Africa is considered a low-seismicity region, with typical natural peak ground acceleration ranging from 0.05 to 0.10 g, according to seismic hazard map of South Africa (Dladla & Ramsamy 2022; Grant-Stuart 2020). Although South Africa experiences low natural seismicity, the presence of mining-induced seismicity and the need to comply with international safety standards make seismic stability analyses essential for TSFs. These analyses are crucial for ensuring the resilience and safety of TSFs under both static and dynamic conditions, thereby protecting nearby communities and the environment (Grant-Stuart 2020). Seismic factors are not considered a significant threat or a motivating factor for adopting FST in South Africa.

4.3 Technology selection

The logistical and technical requirements for transporting, stacking of filtered tailings are essential for ensuring operational efficiency, stability, and environmental sustainability. This component guides users in making decisions about filtration technology selection, water management and seepage, material characterisation, technology selection, stack design, and a stability analysis.

4.3.1 Transportation and stacking

Transportation methodologies for FSTFs in South Africa are influenced by terrain, material properties, haul distances, and economic constraints. A tailored approach is necessary to ensure operational efficiency and cost-effectiveness, particularly given the variability in tailings material characteristics across mining operations. Conveyor systems, haul trucks, and hybrid combinations of these methods are commonly employed.

It should be noted that although FST has not been adopted on large-scale in South Africa, both conveyor systems and haul trucks are mature transportation technologies with hybrid systems increasingly being utilised for their operational flexibility and efficiency. Expert interaction confirmed that the international considerations can be applied into a generic South African context:

- large operations (>15,000 tonnes/day) with short to medium durations (<15 years) lend themselves to transportation by truck
- smaller operations (<15,000 tonnes/day) with medium to long durations (>15 years) lend themselves to transportation by conveyor
- for material to be conveyed the moisture content should be below 20% (material dependant)
- during stacking typical conservative values of the lifts/terraces are 5–10 m and the local slope are equivalent to H:V = 3:1
- 5 m wide berms should be placed on each terrace (to function as transit area and allow for installation of monitoring instrumentation).

Conveyor systems are the preferred method for transporting filtered tailings over long distances in flat or gently sloping terrain, while haul trucks are widely used for shorter distances or rugged terrain in South Africa (Copeland & Teixeira 2019). Trucks are essential for operations like coal ash disposal, where variable moisture contents require precise placement, but they incur higher fuel, maintenance, and labour costs. Hybrid systems, combining conveyors and trucks, are gaining popularity due to their adaptability. For instance, at Skorpion Zinc in Namibia, conveyors handled bulk transport while trucks managed final deposition or stockpiling when conveyor capacity was exceeded, reducing costs while maintaining flexibility (Copeland et al. 2006; Copeland & Teixeira 2019).

Tailings properties heavily influence transportation choices, the following material characterisation parameters can be considered in a South African context:

- Moisture content: tailings with low moisture content (<20%) are generally easier to handle and transport, whereas those with higher moisture content (>30%) can become sticky and prone to chute blockages, particularly in conveyor systems. Most commodities except for some diamond (kimberlite) and heavy mineral sand tailings have moderate filterability.
- PSD: coarse-grained tailings, such as kimberlites from diamond mining, are less problematic during transport compared to fine-grained or clay-rich tailings, which can lead to clogging in conveyors or require additional blending during transport.
- Plasticity and shear strength: high plasticity clays, such as those found in platinum and gold tailings, exhibit poor flow properties and increase the complexity of transportation systems. In contrast, coal ash and diamond tailings have higher shear strengths, making them easier to stack and transport.
- Stickiness and adhesion: zinc tailings with moisture contents above 35% exhibit sticky behaviour, often leading to operational challenges in conveyor systems unless adjustments like steeper chute angles and low-friction linings are made (Copeland et al. 2006).

In South Africa (like the rest of the world), the economic feasibility drives transportation choices. Although conveyors have high initial costs, they offer long-term savings through reduced operational expenses, while haul trucks are less capital-intensive but accumulate higher running costs over time. Hybrid systems optimise these trade-offs, especially in large-scale or long-term operations (Copeland et al. 2006).

Additionally, in South Africa, trucking services are often outsourced to local communities as part of social development initiatives, influencing method selection even when less cost-effective.

4.3.2 Filtration technology selection

To select a filtration technology, the engineer needs to already have the required tailings product specifications and then the filtration technology selection can be explored. The first step would be to select a filtration technology that should comply with the specified moisture content as required for successful transportation and stacking. Although filtered presses are the preferred technology based on throughput, a comprehensive study should be conducted using several dewatering technologies to determine the most suitable technology (based on economics and efficiency). A summary of the different filter technologies and their production rates are provided in Table 1.

Table 1 Summary of filtration technology to be used at different scales in South Africa

	Filter press	Vacuum belt filter	Ceramic disc filter	Belt press	Centrifuge	Horizontal vibrating screens
Small: <1,500 t/day	x	x	x	x	x	x
Medium: 1,500–4,000 t/day	x	x	x			
Large: >4,000 t/day	x	x				

Projects in South Africa that intend to have a single unit throughput requirement of >4,000 tonnes/day should consider filter press or vacuum belt dewatering technologies. For the larger projects (up to 50,000 tonnes/day) filter press technology should be considered. It should however be noted that mineralogy and clay content from different deposits will have an influence on the technology selection. It is therefore crucial that in addition to the above guidelines, representative samples are sent for laboratory scale dewater tests.

The only commodity where FST is applied in South Africa is within coal fines (and coal ash). This poses the question which of the other top commodities could be filtered. The top commodities mined in South Africa are gold, PGM, coal, diamonds, iron ore, manganese, chrome and copper. Each commodity is associated with its own mineralogy governed by the geology as well as the processing steps that created the tailings.

In a South African context, the general baseline chemical properties of tailings could be evaluated based on the framework. Important considerations are the distribution of clays, as high clay contents become increasingly challenging to filter (PSD >40% fines which are <20 µm). Table 2 is an indication of the filterability of some of South Africa's most common tailings by commodity obtained from expert interactions.

Table 1 Ease of filterability of South African tailings based on clay considerations (Vietti 2024)

Commodity	Chemical-clay consideration	Ease of filterability
Witwatersrand Gold	No clays	Can be filtered
PGMs	Clay minerals include talc and kaolinite which have a low MBI (not reactive). Talc is a problem due to its quantity not its reactivity. If there are more than 10% of fine talc material filtration might be challenging	Can be filtered Challenges could be solved by correcting the water quality
Kimberlite	Significant clays	Difficult to filter material, but due to coarse fraction this could be done There is a large chance that the clay/fines will blind the filter cloth
Mineral sands	Significant reactive clays >40% passing 20 µm	Very difficult to filter
Coal	Kaolinite which has a low MBI (not reactive)	Easy to filter
Iron Ore	Contains Kaolinite and Goethite	Easy to filter (differs between different iron ore deposits)

*Active clays include smectite, vermiculite and illites.

The data in Table 2 is not exhaustive and should only be used as a high-level guide. Although the data was based on expert interactions and clay considerations, it is recommended that individual test work (site specific) be conducted to ensure the true reflection of filterability of each commodity. Based on the clay minerals, PSD and percentage fines the materials identified as difficult to filter are kimberlites as well as heavy mineral sands. The process water was also identified as a crucial consideration for tailings chemical characterisation as this could determine if the clays are in a dispersive state or not. It should be noted that water quality should be measured and could be corrected to improve the clay (Vietti, pers. comm., 2024).

4.4 Environmental and regulatory considerations

This component of the framework briefly addresses the environmental and regulatory requirements to South African mining operations. The framework helps ensure that tailings facilities are compliant with local regulations and environmentally sustainable.

South Africa's regulatory framework for tailings management is primarily guided by SANS 10286 (South African Bureau of Standards 1998), which provides a foundation for ensuring the safety and integrity of mine residue facilities. This standard, along with the *Mine Health and Safety Act* (Republic of South Africa 1996), defines roles such as manager, operator, and professional engineer, who are responsible for the design, operation, and compliance of tailings facilities. SANS 10286 has traditionally served as a benchmark for structural safety, hazard classifications, and general management practices for tailings dams in South Africa (MacRobert et al. 2022).

Despite the robustness of these frameworks, South Africa faces unique challenges in tailings management due to water scarcity, complex geotechnical conditions, and regulatory intricacies. High evaporation rates exacerbate water recycling challenges, while windy conditions contribute to significant dust emissions that affect nearby communities. Additionally, acid mine drainage (AMD) from historical tailings dams necessitates costly mitigation measures, such as liners and seepage control systems, further underscoring the need for advanced technologies (Grant-Stuart 2020).

A key challenge in South Africa's regulatory framework is the overlap between the *National Water Act* (NWA), the *National Environmental Waste Management Act* (NEMWA), and SANS 10286, which leads to

compliance inefficiencies (Grant-Stuart 2020). This fragmentation is particularly problematic for legacy facilities, as they were constructed under less stringent environmental and safety regulations. Government Notice R704, issued under the NWA, mandates strict conditions on seepage control and buffer zones, creating challenges in retrofitting older tailings storage facilities to meet these newer standards (Grant-Stuart, 2020). Aligning these national requirements with international best practices, such as the GISTM, could streamline compliance and improve environmental stewardship.

SANS 10286 emphasises the need for stability assessments throughout a TSF's life cycle but does not prescribe fixed Factors of Safety (FoS). Instead, it encourages site-specific evaluations based on factors such as soil conditions, seismic risks, and environmental challenges. While benchmarks typically recommend FoS values of 1.5 for drained conditions and 1.1 for undrained conditions using residual strengths below the phreatic surface, dry-stacked facilities can remain stable with FoS as low as one, if carefully managed (Copeland & Zannoni 2024). However, even with lower thresholds, strong monitoring systems and strict operational controls are essential to ensure facility safety and environmental protection Copeland & Teixeira (2019).

AMD mitigation remains a significant concern. For high-risk facilities, such as those handling hazardous or reactive tailings, liners like compacted clay or geosynthetic materials (e.g. HDPE) are mandatory to prevent seepage and protect groundwater. Similarly, surface water control measures governed by the NWA require integrated systems, including diversion channels and spillways, to manage run-off and reduce erosion. Environmental impact assessments guide the implementation of these measures, with regular monitoring ensuring compliance and safeguarding both the environment and surrounding communities (Grant-Stuart 2020).

From the expert interactions it also became clear that the difference in environmental 'zone of influence' between conventional wet tailings and mechanically placed and compacted FST is significant. For conventional wet TSFs, the zone of influence considers the final height of the dam, with upstream, side, and downstream zones calculated as: 5 × final height, 10 × final height, and 100 × final height, respectively, with a limit of 6,500 m (Dladla & Ramsamy 2022). In contrast, dry-stacked facilities have a much smaller downstream zone of influence, typically twice the height of the facility. This substantially lowers the environmental risks associated with the TSF.

4.4.1 Global Industry Standard on Tailings Management compliance in South Africa

The adoption of the GISTM in South Africa seeks to address gaps in accountability and governance within tailings management systems. By introducing specific roles such as the accountable executive (AE), responsible tailings facility engineer (RTFE), EOR, and an independent tailings review board (ITRB), GISTM ensures that responsibility is clearly assigned at every operational level. These roles not only enhance risk management but also establish technical specialisation and independent oversight, which are critical for ensuring TSF safety and compliance. The integration of the GISTM into South Africa's SANS 10286 standard has been proposed by MacRobert et al. (2022), offering a framework that ensures both compliance with global standards and adaptability to local practices. The framework is illustrated in Figure 6. The solid lines indicate typical appointments, but appointment can also follow the dotted lines.

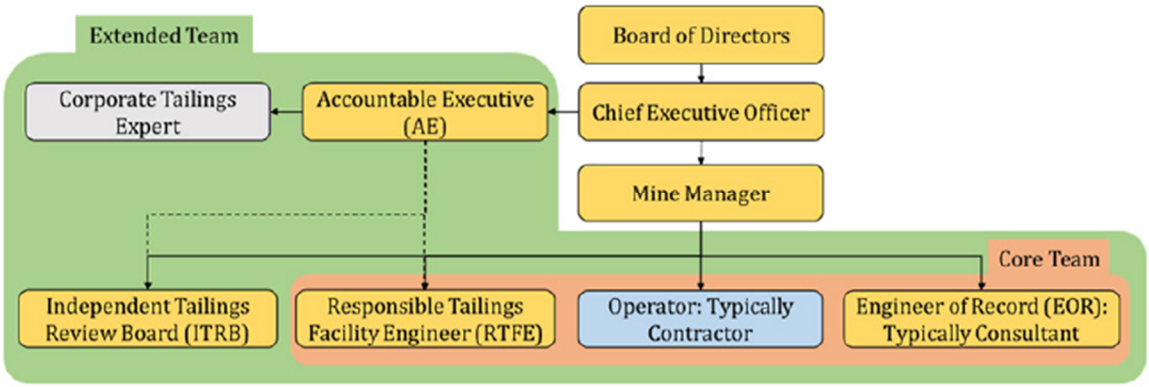

Figure 6 Proposed global industry standard on tailings management, management structures. Figure after MacRobert et al. (2022)

The major difference between the proposed GISTM structure and the SANS 10286 structure lies in role clarity, accountability, and governance. GISTM introduces distinct roles – AE, RTFE, EOR, and ITRB – to ensure clear responsibilities, technical specialisation, and independent oversight (MacRobert et al. 2022).

4.5 Economic feasibility

The economic feasibility of FSTFs in South Africa is influenced by site-specific conditions, regulatory requirements, and broader operational contexts. Capital costs for FSTFs are significantly higher than those for conventional slurry-based tailings facilities due to: advanced filtration systems, compaction equipment, and seepage control measures. While these costs can be offset by long-term savings in water usage, reduced environmental liabilities, and simplified closure processes, the upfront investments remain a major barrier, even for companies with high ESG commitments (Copeland, pers. comm., 2024; Copeland et al. 2023).

Water scarcity is a critical factor driving the adoption of FSTFs. In arid regions, where evaporation exceeds precipitation, dry stacking offers significant water conservation benefits by allowing for the re-use of water extracted during dewatering. Conversely, in high-rainfall areas, the additional costs of drainage and erosion control infrastructure can diminish economic feasibility unless offset by regulatory compliance or long-term closure savings (Copeland et al. 2023).

Copeland (2024) mentioned that the regulatory compliance under South African legislation, such as the NEWMA, further increases costs due to the requirement for liners and seepage control systems in high-risk facilities. These measures mitigate long-term risks, such as groundwater contamination and AMD, reducing future environmental liabilities and closure costs, particularly for reactive or hazardous tailings (Copeland et al. 2023).

Proximity to processing plants is another important consideration. Locating FSTFs near plants reduces transportation costs and improves operational efficiency. For example, a South African platinum mine strategically opted for a smaller, nearby dry stack facility to minimise transport expenses, demonstrating how spatial planning can enhance economic viability (Copeland et al. 2023).

Life cycle costs also play a key role in economic feasibility. While FSTFs require higher initial investments, their compacted nature simplifies closure activities such as reshaping, capping, and revegetation, resulting in lower post-mining costs compared to conventional facilities. Concurrent rehabilitation further reduces dust management and operational expenses over time (Copeland et al. 2023).

Despite these advantages, high costs, particularly for liners, remain the primary barrier to FST adoption. Retrofitting older facilities from wet to dry can be prohibitively expensive – up to nine times the original cost – and is only justifiable when addressing critical risks, such as AMD (Copeland, pers. comm., 2024; Copeland et al. 2023). This underscores the importance of detailed trade-off studies to evaluate cost-effectiveness, considering regional climate, operational needs, and tailings properties.

5 Discussion

The development of this framework represents a significant advancement in addressing the challenges associated with FST in South Africa. By integrating global best practices with localised considerations, the framework offers a structured approach to guide decision-making for FST adoption. Key components such as material characterisation, site-specific conditions, technology selection, environmental and regulatory alignment, and economic feasibility provide a comprehensive basis for evaluating FST implementation.

However, expert feedback highlights critical barriers to FST adoption in South Africa. Cost remains the dominant factor, with high capital investments in dewatering technologies and mandatory liners creating financial hurdles, even for mining companies committed to high ESG standards. These challenges underscore the need for targeted solutions that address cost and technical feasibility, particularly in the South African context, where water scarcity is a pressing concern.

The framework's adaptability is a key strength, enabling users to conduct trade-off analyses between conventional and filtered tailings management approaches. While general in structure, the framework provides a foundation that can be customised to the unique conditions of individual mining sites, such as climatic variations, tailings mineralogy, and operational constraints. For instance, the inclusion of tools like the MBI and classification plots for fines content and clay activity, enhances the framework's relevance to South African materials.

Nevertheless, limitations exist. The reliance on secondary data and global best practices reflects the lack of region-specific research. Future validation through field trials and collaboration with South African mining stakeholders is essential to refine the framework and improve its applicability. Additionally, the framework should be expanded to explore cost-reduction strategies, such as alternatives to liners, innovative dewatering technologies, and optimised stack designs.

Despite these challenges, the framework contributes to the growing body of knowledge on sustainable tailings management and aligns with the global shift toward environmentally responsible mining practices. By addressing local conditions and promoting critical decision-making, it has the potential to guide the South African mining industry toward adopting safer and more sustainable tailings management solutions.

6 Conclusion

This paper presents a preliminary framework tailored to the unique environmental, regulatory, and operational challenges of FST implementation in South Africa. By focusing on material characterisation, site-specific conditions, technology selection, environmental and regulatory compliance, as well as economic feasibility, the framework provides a structured pathway for assessing the viability and sustainability of FST systems.

The framework highlights the importance of trade-off analyses to balance cost, water scarcity, and environmental stewardship. It serves as a decision-making tool for stakeholders, enabling the trade-off between FST and conventional tailings methods. While high initial costs and technical challenges limit the widespread adoption of FST, the framework provides a foundation for addressing these issues through targeted research and baselining.

Future work should focus on validating the framework through field trials and collecting commodity-specific data on tailings characteristics and performance. This will ensure that the framework remains relevant and adaptable to South African mining contexts. Validating the framework will build confidence and discussions around this preliminary version is encouraged. Additionally, research into cost-reduction strategies, such as innovative liner alternatives and enhanced dewatering technologies, will be critical to overcoming financial barriers.

In conclusion, this framework offers a practical and scalable tool for advancing sustainable tailings management in South Africa. By encouraging critical thinking and fostering trade-off studies, it supports the

adoption of FST as a viable alternative to conventional tailings storage, contributing to safer, more efficient, and environmentally responsible mining practices.

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