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Central thickened discharge scheme for Ma'aden's Mansourah-Massarah Gold Project

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Abstract

This paper provides a comprehensive case study detailing the inception, development, commissioning, and initial operations of a state-of-the-art tailings management facility in the Mansourah-Massarah Gold Project, situated within the arid terrain of the Kingdom of Saudi Arabia and operated by the Saudi Arabian mining company Ma'aden. With an annual average rainfall of a mere 80 mm and evaporation rates of 5,800 mm per annum, the mine relies on a water supply sourced from Taif town, a distance of 330 km.

Commencing operations in 2022 and projecting a life span of 12 years, this operation is set to generate two types of tailings: oxide and sulphide (fresh) tailings, with a combined nominal production rate of approximately 4 million tonnes per annum. Given the arid setting and the substantial cost of water supply exceeding $4 per cubic metre, the rigorous management of water resources stands as a pivotal factor in tailings management selection. The primary objectives in tailings management for this project encompass the following key considerations:

1. *Water conservation: prioritising the preservation of water resources.*
2. *Safe and efficient tailings storage: ensuring secure and efficient containment of tailings.*
3. *Cost optimisation: striving for cost-effective solutions.*

The recommended strategy for this project involves the installation of a paste thickener in conjunction with central thickened discharge storage of the paste-thickened tailings. The tailings management approach for this project will be implemented in three progressive stages.

This paper explores the following facets of the project:

1. *Tailings management concept and tailings properties.*
2. *Tailings distribution and beach slope evaluation.*
3. *The water management system.*

For this project, a 40 m-diameter paste thickener has been employed, targeting an underflow solid concentration of approximately 65% for fresh tailings and 57% for oxide tailings. Initially, it was estimated that the maximum beach slope would be 1.3% during the commissioning phase, gradually improving to 2.3%. As of the time of preparing this article, the first beach survey has been conducted, suggesting that the actual achieved beach slope is approximately 2.1%, surpassing initial expectations.

Keywords: *tailings management, central thickened discharge, gold tailings*

1 Introduction

The Mansourah-Massarah Gold Project, located within the Central Arabian Gold Region in the Kingdom of Saudi Arabia, holds strategic significance due to its contribution to the country's economic development. The site is positioned approximately 320 km northeast of Taif on the route to Riyadh and 35 km southeast of Hufairah. Figure 1 provides an overview of the mines' spatial arrangement.

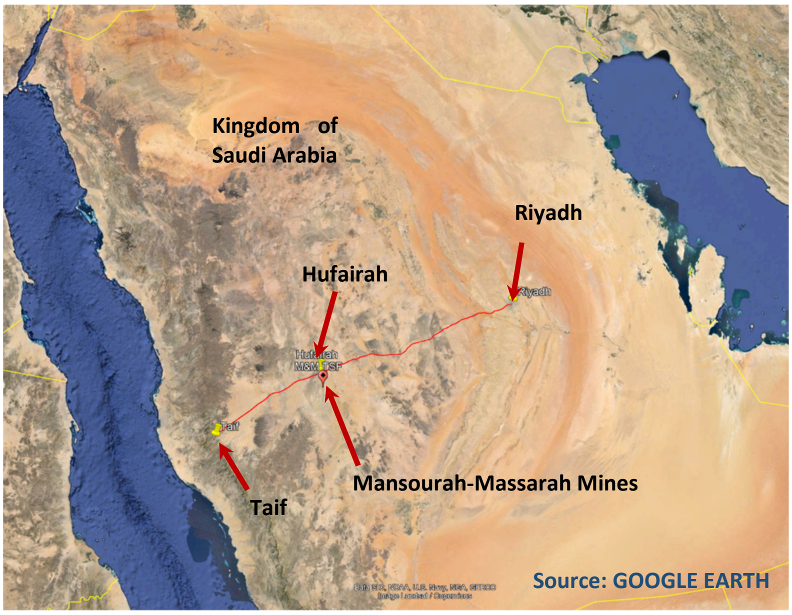

Figure 1 Locality plan of Mansourah-Massarah gold mines

The Mansourah-Massarah Gold Project is characterised by the presence of two distinct ore types: oxide ore and sulphide (fresh) ore. The operational dynamics involve a nominal average overall tailings production rate of 4 million metric tonnes per annum (Mtpa). This production is composed of approximately 83% fresh tailings and the remaining 17% in the form of oxide tailings. Over the projected mine life of approximately 12 years, the cumulative tailings production is estimated to reach around 45 million metric tonnes.

A noteworthy aspect of the tailings production schedule is the temporal distribution of oxide tailings. The majority of oxide tailings are anticipated to be generated in key operational phases, specifically in years 1, 6, and 12.

2 Project overview

The comprehensive tailings management facility (TMF) for the Mansourah-Massarah Gold Project encompasses various integral components, each designed to ensure efficient tailings handling and environmental stewardship. Mainly ANCOLD standard is used for the design of the TMF. The core elements of the TMF are as follows:

- Tailings paste thickener (it should be noted that there is only one thickener and alternate between oxide and sulphide). Paste thickener is utilised in this project with the aim of water conservation as outlined by Vietti et al. (2010):
  - Tailings undergo thickening in a 40 m diameter deep cone (paste) thickener (supplied by Outotec).
  - Initial test results from the thickener supplier indicated a design underflow solids concentration of 65% for fresh tailings and 57% for oxide tailings, with the flocculant consumption dosage of 15 g/t of tailings.
  - Unit solids loading rate is considered to be approximately 0.5 t/(m^2/h).

- Tailings delivery infrastructure:
  - Consists of two trains of centrifugal pumps (one operational and one backup), and each train has three pumps in series.
  - A rubber lined 250 mm steel pipeline with an overall length of 1.5 km and with an overall elevation difference of approximately 30 m.
- Tailings distribution system (to provide a central distribution system as outlined by Pirouz et al. 2020):
  - A pressurised vessel located at the centre of the tailings storage facility (TSF). Tailings are distributed through 10 outlet pipes arranged around a central platform with planning for only five open spigots at each point in time.
- Tailings delivery ramp and access road:
  - Essential for vehicular access during operation, inspection, and maintenance, and ensures efficient transportation to and from the discharge platform.
- TSF:
  - A central thickened discharge (CTD) scheme for the containment and storage of tailings. It is to be developed in three main stages with perimeter embankment radii of 500, 900 and 1,200 m. Entire TSF area is lined by a high-density polyethylene (HDPE) liner with a geotextile underlay, as instructed by the KSA environmental authorities to minimise the risk of seepage.
- Tailings drainage management:
  - Includes tailings drainage collection pipelines (slotted HDPE pipes) inside the TSF to collect and discharge potential consolidated water with a sand layer at the low point aids in draining remaining water into slotted HDPE pipes.
- Decant structure and pipeline:
  - The decant structure is a concrete flume equipped with progressively placed lids to prevent tailings entry. It has a 500 mm steel pipe that conveys water from the decant structure to the decant channel on the downstream of the TSF.
- Perimeter embankment:
  - Constructed with locally sourced materials, utilising excavation and mine waste (generally sandy and gravely material). With a 500 m radius from the tailings discharge platform in Phase 1 and 900 and 1,200 m for future phases.
  - The entire perimeter embankment is lined by a HDPE liner, with a geotextile underlay.
- TSF spillway:
  - 50 m wide spillway (maximum capacity of 17 m^3/s) located on the southeastern side of the perimeter embankment. Overflow will be directed to the decant channel to be stored in the evaporation pond
- Evaporation pond. It should be noted that a decant return water system has not been included in the original design. This return water system is being designed at the time of the preparation of the paper:
  - Serves as the final destination for decant and surface runoff water from the TSF. there will be two stages of the evaporation pond construction, Cell 1 to be constructed as part of Phase 1 and Cell 2 as part of Phase 2. Cell 1 with a capacity of 100,000 m^3 and Cell 2 with a nominal capacity of 260,000 m^3.

An aerial photograph of the Phase 1 TSF during initial operations is presented in Figure 2.

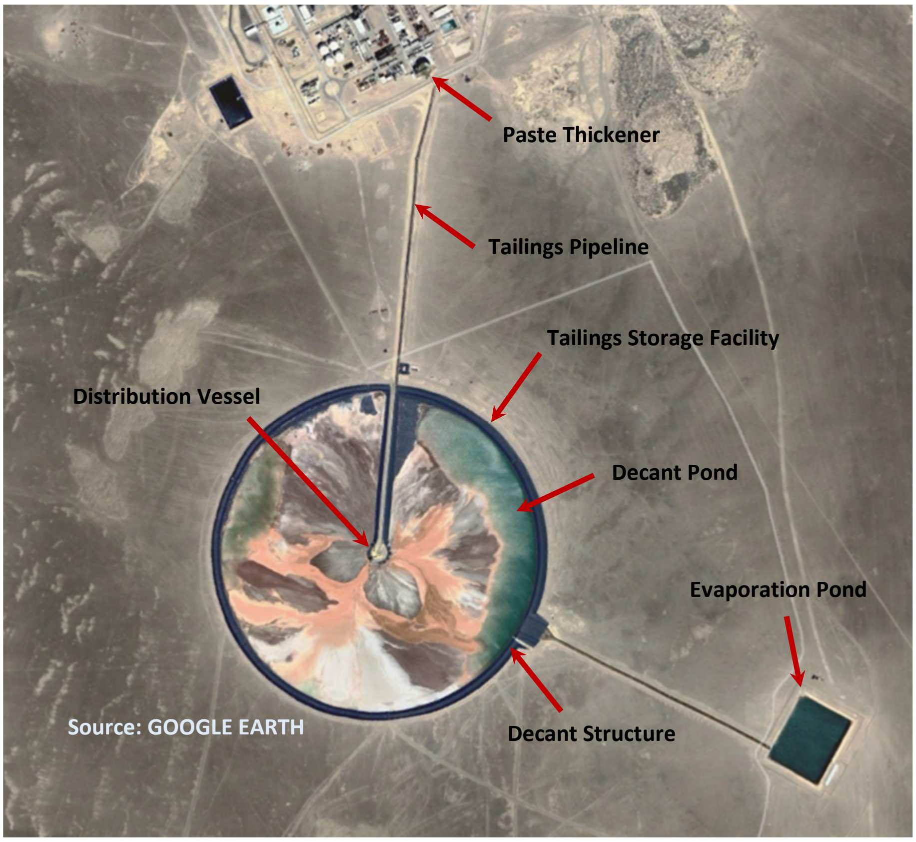

Figure 2 Aerial photograph of tailings storage facility Phase 1

3 Tailings properties

Tailings have been tested at different stages of the project. The tailings particle size distribution from three tests is shown in Figure 3. It should be noted that the 2020 fresh sample was from the bench test at the time and 2023 fresh and oxide samples are actual samples from the production.

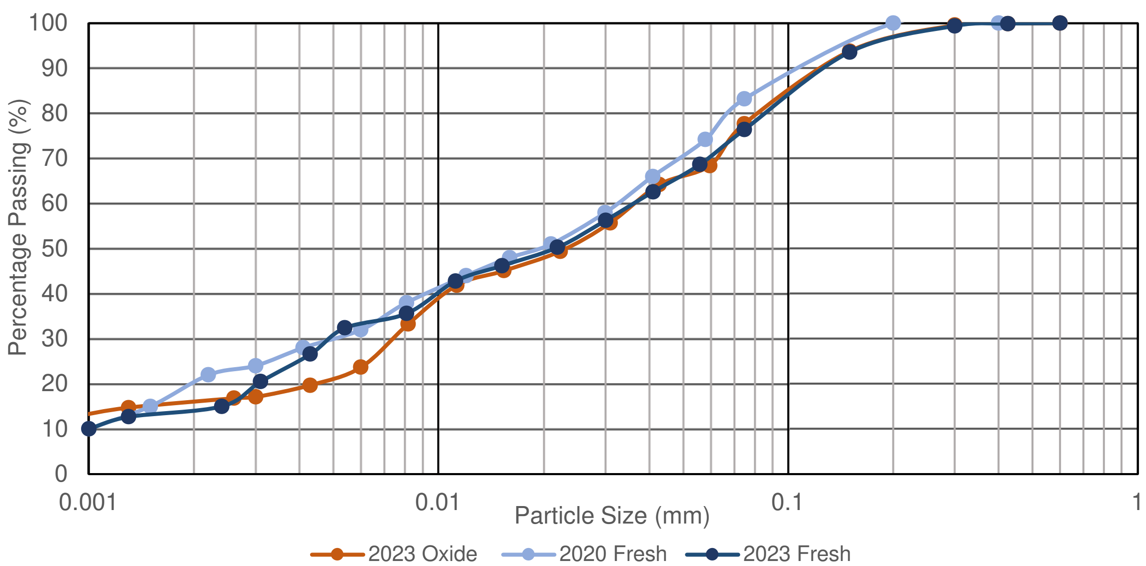

Figure 3 Tailings particle size distribution

The measured Atterberg limits for different tailings are tabulated in Table 1, giving all the tailings types a USCS classification of sandy clay (CL). The fresh tailings have a soil particle density of 2.85 and the oxide tailings density is measured at 2.8. It should be noted that at this early production stage, the geotechnical difference between fresh and oxide tailings appears to be minimal.

Table 1 Measured tailings Atterberg Limits

Description	Fresh (2020 tests)	Fresh (2023 tests)	Oxide (2023 tests)
Plastic limit	20	21	17
Liquid limit	29	32	28
Plasticity index	9	11	11
Classification	CL	CL	CL

Tailings yield stress, consistency index and flow index (measurements are done using a Thermo Haake VT550 Viscotester) versus tailings solids concentrations are shown in Figures 4, 5 and 6, respectively. These parameters are related to Herschel–Bulkley fluid model represented by the following equation:

$$\tau = \tau_y + K\gamma.^n \quad (1)$$

where:

τ = shear stress

τ_y = yield stress

K = consistency index

$\gamma.$ = shear rate

n = power-law index.

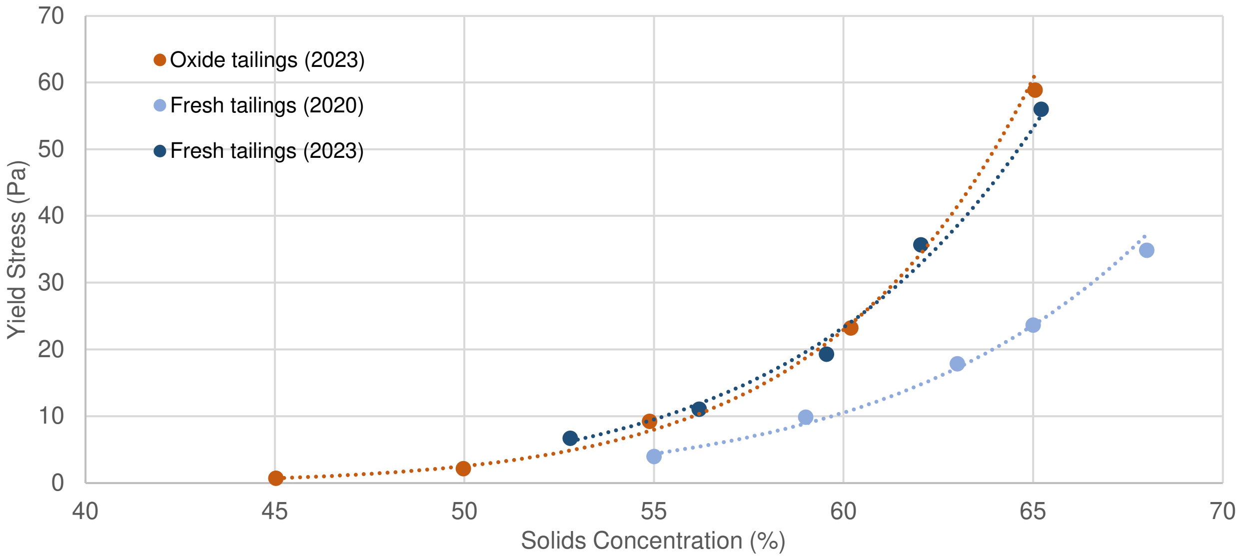

Figure 4 Tailings yield stress versus solids concentration

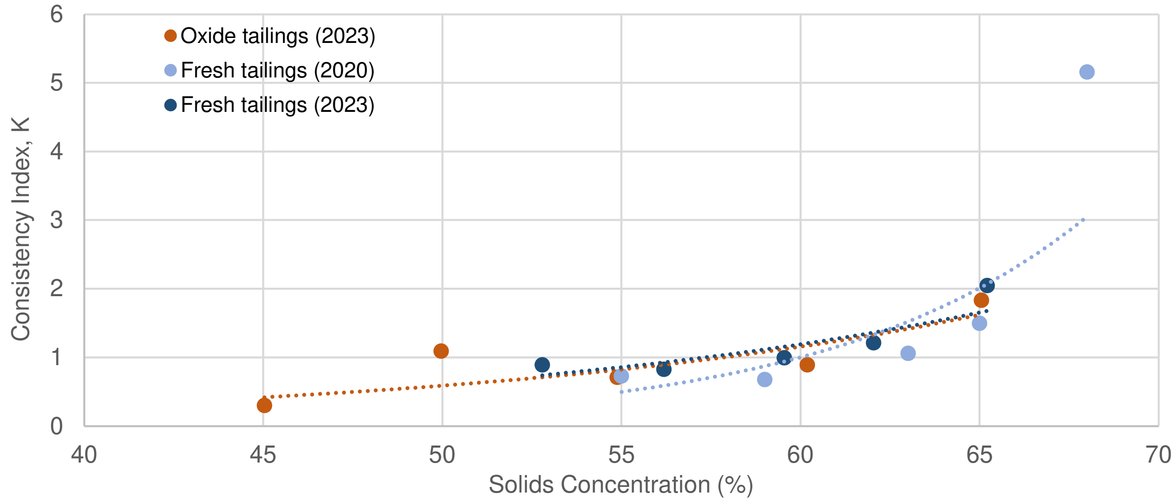

Figure 5 Tailings consistency index versus solids concentration

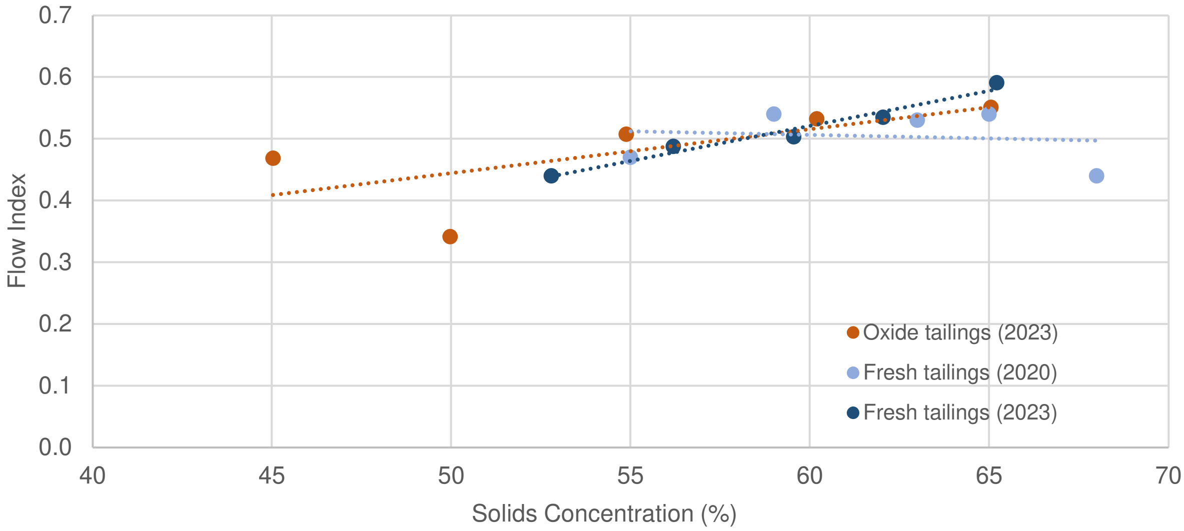

Figure 6 Tailings flow index versus solids concentration

4 Climate conditions

Mansourah-Massarah mines (the two mine pits are located at an approximate distance of 10 km from each other) are located in an arid environment (BWh - dry arid climate found in low latitude deserts, in accordance with Köppen–Giger climate classification (Peel et al. 2007)) with average annual rainfall of 80 mm/yr and evaporation 5,800 mm/yr. Most of the rainfall occurs in Spring (March to May) as presented in Figure 7.

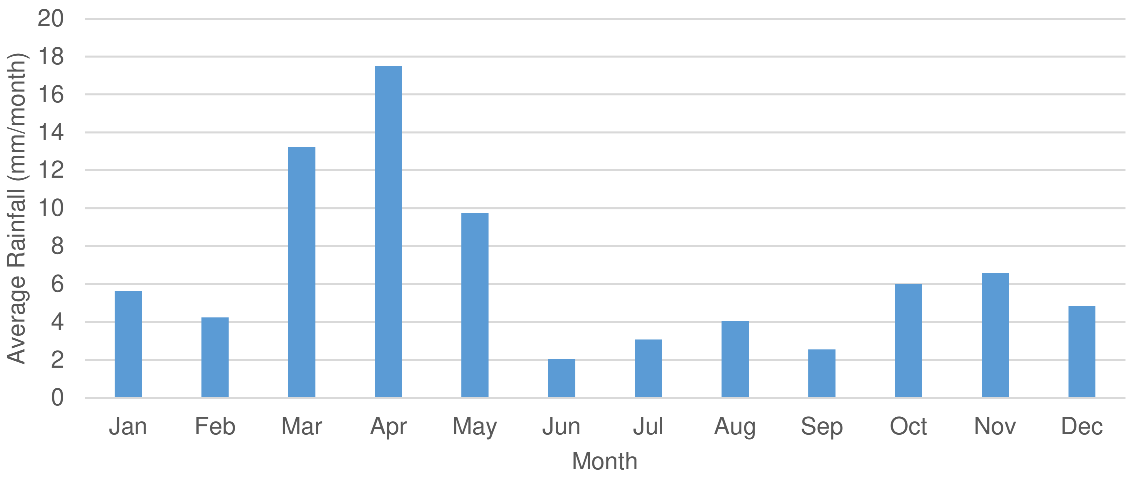

Figure 7 Annual distribution of rainfall at Mansourah-Massarah Gold Project

5 Design considerations

5.1 Distribution system and beach slope evaluation

The adopted scheme for tailings management at the Mansourah-Massarah Gold Project is the CTD method. This approach leverages a central discharge point, resulting in the accumulation of thickened tailings in the form of a low conical hill. The pivotal factor for the success of the CTD scheme lies in achieving an optimal (achievable considering all the constraints) beach slope.

In the context of CTD, the beach slope is a critical parameter influenced by two primary factors: tailings properties and volumetric flow (Pirouz 2014). Tailings properties encompass particle specific gravity (SG), particle size distribution, plasticity and, notably, rheological properties. Among these, rheological properties, representing the tailings' flow behaviour are particularly crucial. The representation of rheological properties is encapsulated by the concept of 'solids concentration'. This parameter serves as a key indicator of the tailings' flow characteristics. Figure 8 visually articulates the intricate relationship between solids concentration and the predicted beach slope (based on ATC William's in-house beach slope prediction model), specifically at the steepest segment of the beach profile. Since the majority of the tailings are fresh tailings, Figure 8 represents the fresh tailings beach slopes.

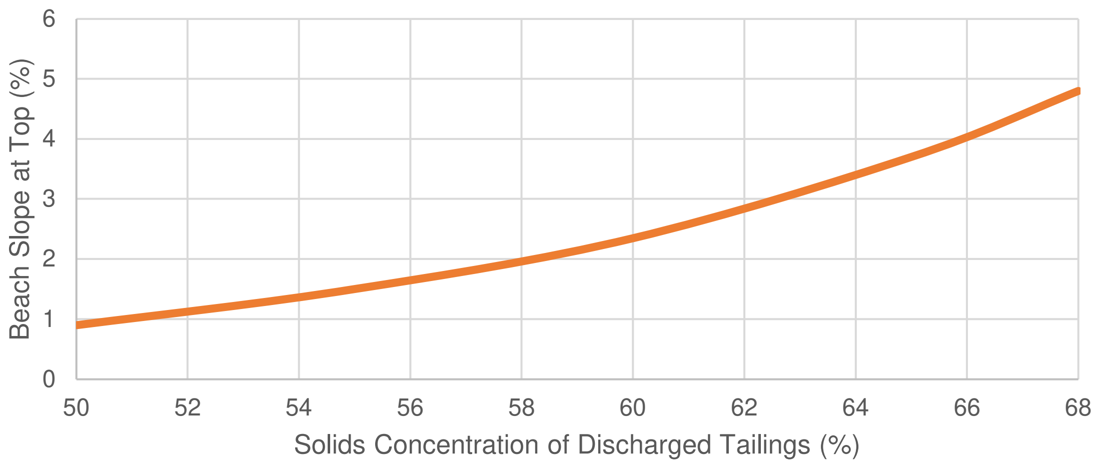

Figure 8 Relationship between the solids concentration and beach slope at the top

In addition, as a general rule, the achieved beach slope crucially depends on the volumetric flow from each discharge spigot forming individual channels on the beach. Figure 9 illustrates the interplay between the volumetric flow of each spigot at 65% solids concentration and the predicted beach slope at the apex of the profile (the total volumetric flow of tailings at 4 Mtpa and 65% solids is approximately 450 m^3/hr, i.e. a single point discharge). The merging of individual channels impacts the resulting beach slope, reflecting the combined flow characteristics rather than those of individual spigots. This dynamic relationship underscores the need for a nuanced understanding of volumetric flow dynamics, guiding the optimisation of the discharge strategy. By considering both rheological properties and volumetric flow, Mansourah-Massarah ensures an effective and successful CTD implementation, aligning operational objectives with tailored tailings management goals.

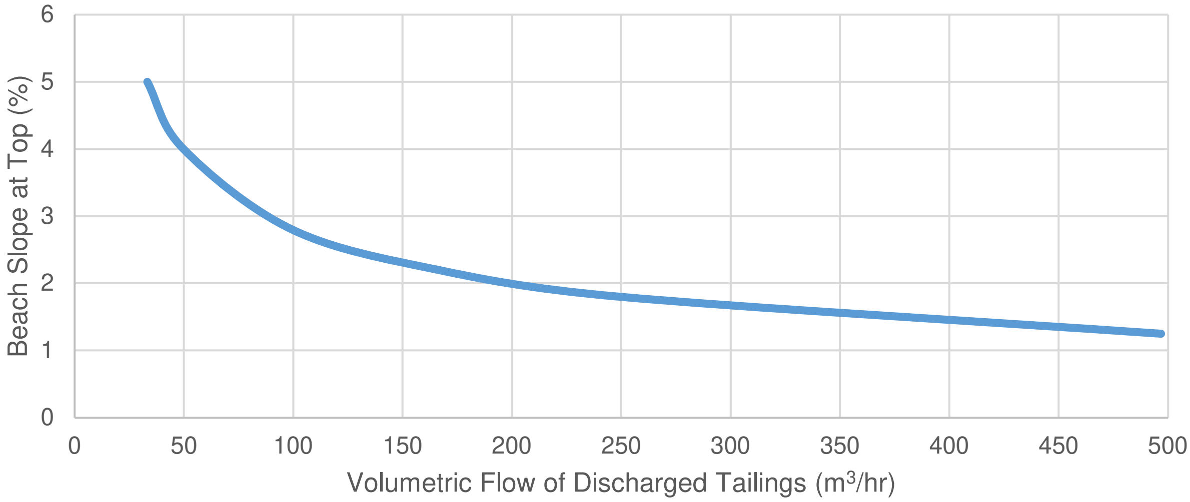

Figure 9 Relationship between the volumetric flow and beach slope at the top

Integral to the success of the CTD scheme at the Mansourah-Massarah project is the design and implementation of an innovative distribution system. A distinctive distribution vessel, as depicted in Figure 10, has been engineered to optimise the even distribution of thickened tailings. This pressurised vessel efficiently allocates the flow into 10 discharge spigots, with the operational plan specifying the activation of only five spigots at any given time.

Figure 10 Utilised distribution vessel at Mansourah-Massarah project

The utilisation of this advanced distribution vessel is a strategic response to the critical role of even distribution in achieving an optimal beach slope. The pressurised mechanism ensures a controlled and uniform discharge, mitigating the risk of uneven channel formation on the beach. By allowing flexibility in the activation of discharge spigots, the design accommodates dynamic variations in volumetric flow, contributing to the overall efficiency and adaptability of the CTD system.

On this basis, the adopted beach slopes in this project are presented in Table 2.

Table 2 Adopted beach slopes

Beach slope/month	Upper slope	Middle slope	Lower slope	Runout
Month 1 to 13	1.30%	1.00%	0.75%	0.50%
Month 14 to 29	1.80%	1.35%	1.00%	0.50%
Month 30 to 51	2.30%	1.80%	1.35%	0.50%

Beach slope prediction methodology is based on Pirouz (2014) and the length of each section is estimated based on the predicted performance of the paste thickener as outlined by Seddon et al. (2018).

Also, as noted by Seddon et al. (2018), the beach profile incorporates a characteristic concavity, being steepest at its upper segment and gradually tapering down towards the lower part of the beach. This concavity is predominantly influenced by the daily variability in thickener performance, a factor acknowledged in the design considerations of the CTD scheme.

The runout slope, delineated in Table 2, pertains to the region proximate to the decant pond featuring an intentionally flat beach slope. This specific area typically results from the discharge of off-spec material, notably dilute tailings, during instances of thickener downtimes, underperformance, or system flushing.

The decision to adapt flatter beach slopes, particularly in the initial years of operation, is rooted in strategic considerations. The planned commencement of mining oxide ore at the project's outset and the anticipation of potential challenges in operating the paste thickener and distribution vessel at their design intent during the initial months contribute to this adaptation. This forward-thinking approach aligns with the operational realities and ensures the efficient management of tailings, underscoring Mansourah-Massarah's commitment to flexibility and adaptability in the execution of the CTD scheme.

5.2 Tailings deposition and staging

The tailings deposition strategy at the Mansourah-Massarah project encompasses a three-stage construction plan for the TSF with varying perimeter embankment radii. The central point of each stage remains consistent – the discharge platform – with alterations limited to elevating the platform at different stages. Tailings deposition commenced into the Start-up (Stage 1) TSF in September 2022, featuring a perimeter embankment with a 500 m radius (inner perimeter embankment) and a maximum height of 6.0 meters at RL 907.0 m. This phase includes the construction of the tailings pipeline ramp up to a maximum elevation of RL 912.5 m and the development of the evaporation pond (Cell 1) with a capacity of 100,000 m^3, accommodating approximately 12 months of tailings deposition, totalling around 2.4 million cubic metres.

To facilitate continued operations, the next stage involves the construction of an intermediate perimeter embankment (Stage 2) with a radius of 900 m and a maximum height of 6.7 m at RL 907.0 m. This stage is designed to be ready for tailings overflow from Stage 1, with the tailings pipeline ramp raised to a maximum elevation of RL 918.00 m. The Stage 2 embankment is poised to contain approximately 10.5 million cubic metres of tailings, sustaining operations for 44 months. The construction of Stage 2 is proceeding at the time of the preparation of this article (December 2023) and is planned to be completed by early 2024.

By month 43, the tailings pipeline ramp is slated for elevation to RL 924.0 m, anticipating the subsequent construction of the outer perimeter embankment (Stage 3) with a radius of 1,200 m and a maximum height of 8.6 meters at RL 907.5 m. This stage, including the construction of the tailings pipeline ramp to a maximum elevation of RL 929.5 m, accommodates tailings overflow from Stage 2. The development of evaporation pond (Cell 2) with a capacity of 260,000 m³ completes Stage 3, securing the TSF's capacity to contain tailings until the end of the mine's operational life. Figure 11 provides a visual representation of the sequential tailings deposition plan, illustrating the staged construction and evolving footprint of the TSF.

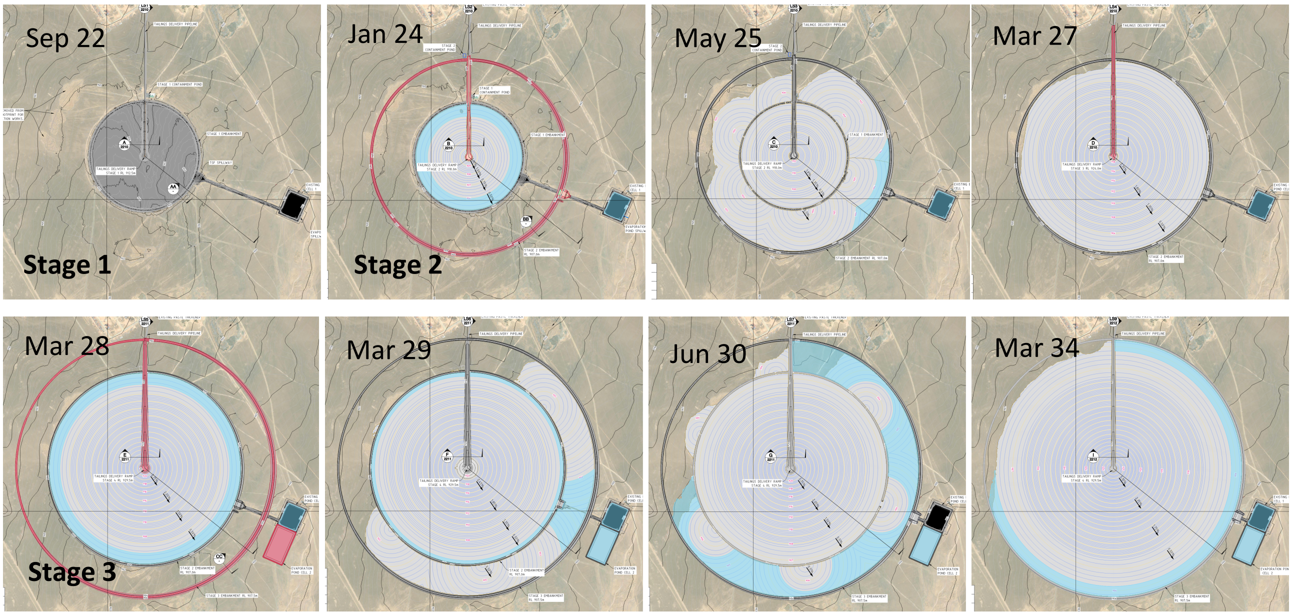

Figure 11 Sequence of tailings deposition at Mansourah-Massarah project

6 Operational outcomes

In July 2023, an aerial beach survey was conducted at Mansourah-Massarah, yielding observed beach slopes detailed in Table 3. Notably, the average observed beach profile is very close to the final design (Table 2) and the overall average slope stands at 1.35%.

Table 3 Measured beach slopes

Beach slope/month	Upper slope	Middle slope	Lower slope	Runout
July 2023	2.10%	1.80%	1.00%	0.50%

Furthermore, the integration of Sentinelhub satellite imagery (https://dataspace.copernicus.eu), available at five-day intervals since the initiation of operations, adds a dynamic dimension to the monitoring process. Leveraging this imagery, the average number of individual self-formed channels on the beach and the area of the decant pond have been indicatively estimated. This is undertaken by using the 'moisture index' images, some of which are illustrated in Figure 12. A review of this figure (supported by site visits) suggests that on average, four self-formed channels have been observed in this period.

This multi-faceted approach, combining on-the-ground beach surveys with satellite-based assessments, reinforces Mansourah-Massarah's commitment to real-time monitoring and adaptive tailings management. The synergy of these methodologies offers a holistic understanding of the CTD system's performance.

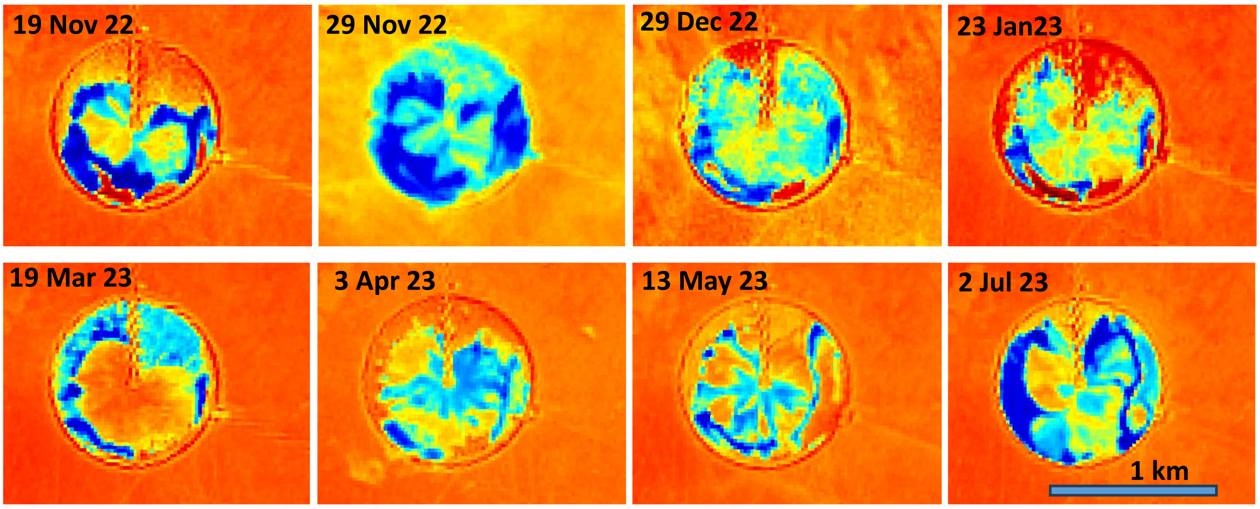

Figure 12 Moisture index images at Mansourah-Massarah project

Figure 13 (should be noted that this figure is prepared for four discharge spigots) and associated observations suggest average solids concentrations of approximately 53% for oxide and 60% for fresh tailings during this period, slightly deviating from design specifications.

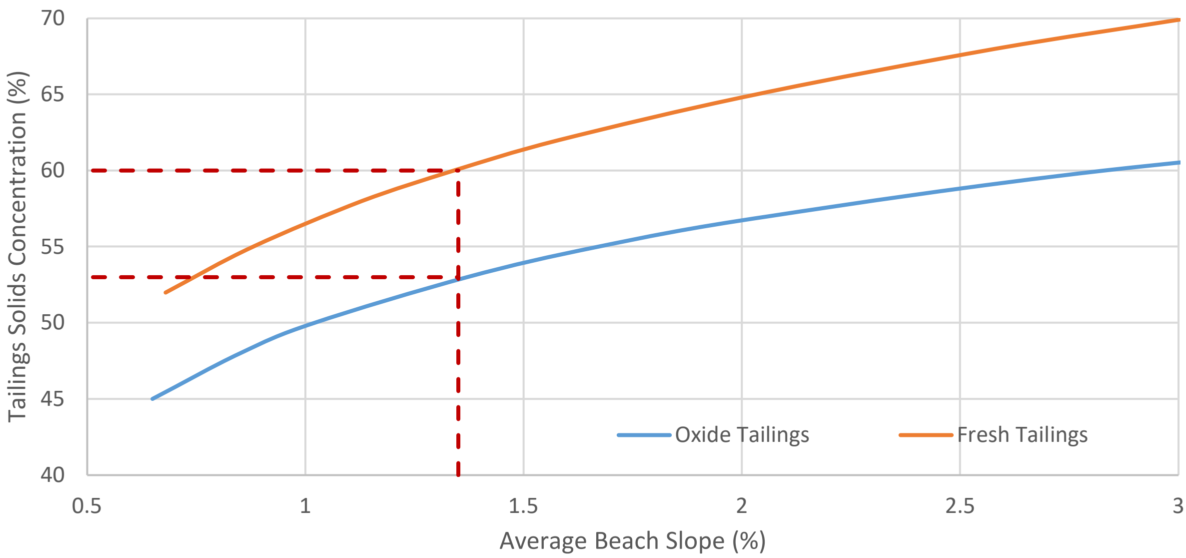

Figure 13 Relationship between beach slope and solids concentration for fresh and oxide tailings and four discharge channels

With a similar approach (utilising the aerial images), the area of the decant pond has been measured on various days and the result is presented in Figure 14.

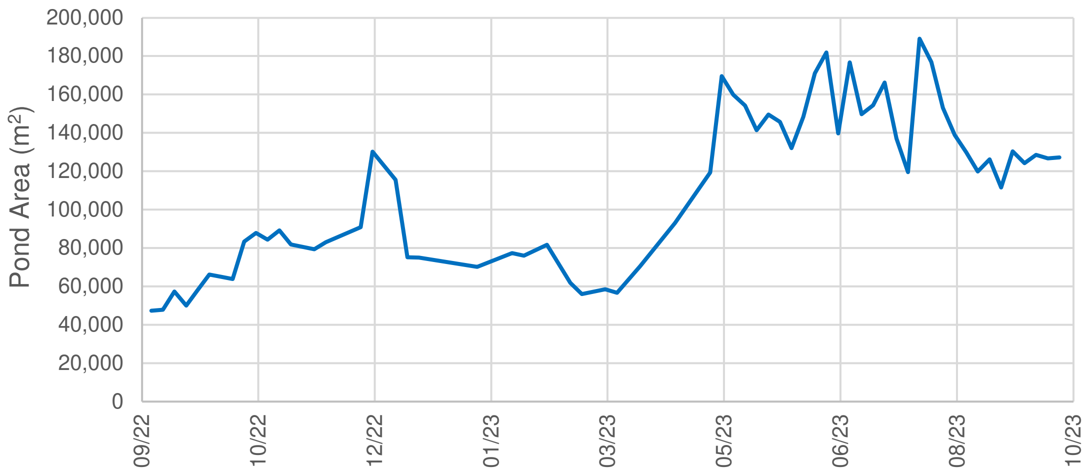

Figure 14 Fluctuation of the decant water pond area on various days

As of December 2023, no reliable in situ density data was available, leading to the utilisation of a design assumption ranging from 1.3 to 1.6 t/m³.

The enhanced beach slopes offer the advantage of accommodating more tailings within the same footprint, leveraging a higher head of beach. Nonetheless, this optimisation comes with an extra cost, as the need for higher tailings delivery elevations translates into increased static head for the pumps. By recognising these complexities, a critical need to evaluate the impact of the paste thickener's performance on the overall tailings management scheme arises.

This inquiry becomes crucial in assessing the delicate balance between beach slope optimisation, operational extensions, and the associated hydraulic considerations. The quest for an optimised tailings management strategy aligns with Mansourah-Massarah's commitment to adaptability and continuous improvement, ensuring the project's resilience and sustainability in the face of evolving operational dynamics.

7 Water management

In the initial months of TSF operation at Mansourah-Massarah, an excess of water in both the decant pond and the evaporation pond has been attributed to various factors. These factors include the discharge of freshwater into the evaporation pond before and during plant commissioning, paste thickener underperformance, and the disposal of brine water into the TSF. Figure 15 shows the proportion of the input of various water sources to the decant pond on an ongoing basis.

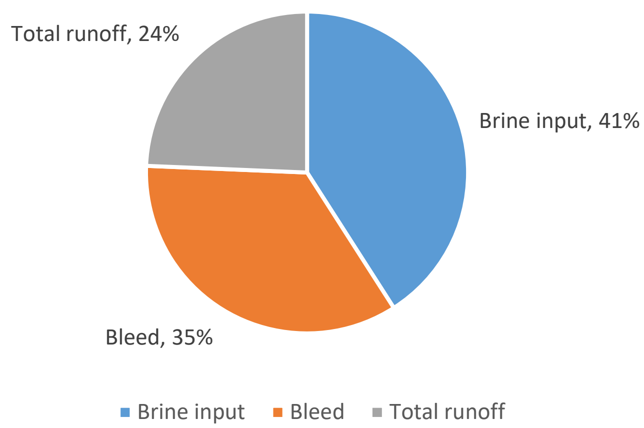

Figure 15 Percentage of input of water to the decant pond

Although the water balance model calibrated with this information exhibits a good fit, it underscores the importance of managing excessive water in the ponds.

Figure 16 presents an overall flow diagram that illustrates the holistic water management scheme at the Mansourah-Massarah project. The proposed water treatment plant and the decant return water system are depicted with a dashed line and in red colour.

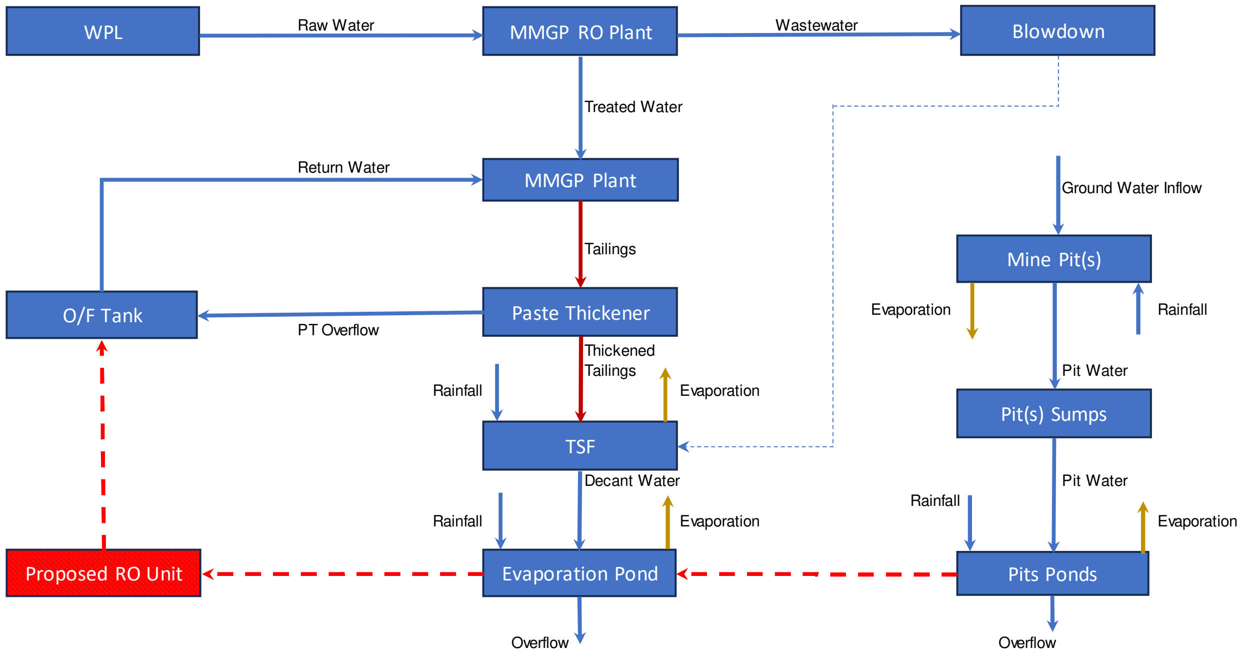

Figure 16 Holistic water management scheme at Mansourah-Massarah project

8 Conclusion

In summary, several key conclusions emerge from the Mansourah-Massarah Gold Project:

- CTD, if designed properly, emerges as a successful tailings management scheme, particularly well-suited for flat and arid environments.
- The implementation of the proposed pressurised distribution system has proven successful, significantly contributing to the effectiveness of the overall tailings management strategy and attained beach slope profile.
- Designing and operating tailings management schemes, especially CTDs, demand the expertise of competent and experienced teams to ensure optimal performance.
- Acknowledging and addressing potential extraneous water inputs and variability in performance of thickeners, especially during commissioning and early operation, is crucial for the success of thickened tailings schemes and CTDs.
- Successful operation of a CTD scheme requires ongoing monitoring and assessment, enabling the identification of emerging opportunities and the mitigation of potential risks. As an example, daily observation would help in recognising if merging of the streams occur and whether additional valves need to be opened.
- Continuous testing of both tailings (such as thickener underflow solids concentration and rheological properties) and water (chemical composition to check the suitability for re-use) is imperative for informed decision-making throughout the operation of a TMF, ensuring adaptability and sustained success in tailings management.

- Tailings and water management in a mine are closely interrelated, demanding a holistic approach to both. One cannot be handled without the other, necessitating a comprehensive approach to tailings management, particularly in a CTD scheme.

Acknowledgement

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