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The place for filtered tailings and stacking in the search for safe and sustainable tailings management

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Abstract

Tailings production, storage and management are integral parts of mineral processing operations, but tailings storage facility (TSF) failures have become a tragic part of the minerals processing industry. The amount of water in the tailings material deposited (in slurry form) and in the TSFs during operation are common factors in many TSF disasters, as the tailings and associated water can flow freely when a breach of containment occurs. In recent years, there has been intensive debate and interest in improved and alternative methods of tailings management, such as thickened paste and filtered tailings. However, the shift to low water content approaches such as filtered tailings storage (often termed dry stacking) continues to be hampered by uncertainties and misunderstandings on the issues and benefits in terms of feasibility, engineering performance, the scale of operation, cost effectiveness etc.

The paper discusses the place for filtered tailings by providing practical insights obtained from the development of what is currently the largest filtered tailings storage facility (FTSF). Design considerations from dewatering processes of thickening and filtration, material handling, disposal, and operation management of the FTSF are discussed. Key learnings on design process, performance criteria, in situ behaviour of filtered tailings, operational control requirements and cost are presented to illustrate the benefits, issues, and applicability of this tailings management option.

The paper demonstrates that tails filtration and dry stacking are feasible in terms of engineering performance and scale of operation. Advancements in filtration technology, material handling and disposal equipment have made it suitable for high throughput operations with reduced risks. Careful design considerations of tailings material characteristics and application of operating discipline result in cost-effective FTSF operation.

Filtered tailings deposited in a partially saturated or unsaturated state, maintain this state with low risk of water table developing within the FTSF. Tailings filtered to high moisture contents and deposited into the FTSF tend to maintain a saturated state over time and should be controlled to the minimum during operation.

Operating costs, although higher than conventional wet tailings management, are still reasonable when lifecycle risks and costs are considered. In low rainfall areas or where conventional wet tailings failure risks are high, filtered tailings and dry stacking should be explored.

Keywords: *filtered tailings, dry stack, unsaturated*

1 Introduction

1.1 Tailings storage facilities

The current methods of mineral extraction rely on water-based methods to separate the minerals from the waste (tailings) during processing. After mineral extraction, the conventional approach is to deposit the tailings in a slurry form into purpose-built tailings storage facilities (TSFs). TSF failures have become a tragic part of the minerals processing industry. A review of failures over the last 50 years shows that failures occur across commodities and across continents and countries irrespective of the level of advancement in design standards, maturity of tailings practice, or regulatory compliance standards in place.

The amount of water in the tailings material deposited and in the TSF during operation, in combination with inadequate management of tailings water, are common factors in many TSF disasters as the tailings and associated water can flow freely when breach of containment occurs. The risks with conventional slurry tailings have generated intensive debate and interest in improved and alternative methods, such as thickened paste and filtered tailings, for safe and sustainable management. However, the shift to low water content approach such as tailings filtration and stacking, commonly termed 'dry stacking' (which is a misnomer), is hampered by uncertainties and misunderstandings on issues and benefits in terms of feasibility, engineering performance, scale of operation, cost effectiveness etc. While tailings filtration and stacking may not have universal application, in some operations, this option will improve or eliminate the lifecycle risks associated with conventional wet tailings. The debate on filtered tailings and dry stacking occurs in both mining businesses and the tailings technical community.

To contribute to the debate, this paper discusses the place for filtered tailings in the search for safe and sustainable tailings management by presenting the experience and practical insights obtained from the development of what is currently the largest operational filtered tailings storage facility (FTSF). Considerations from dewatering processes of thickening and filtration, material handling, disposal and operation management are discussed. Key learnings on design, performance criteria, in situ behaviour of filtered tailings, FTSF operational requirements and costs are discussed.

1.2 Tailings continuum

Tailings exist in different states depending on the water or solids content. Figure 1 (Cacciuttolo & Marinovic 2022, Davis 2011) shows the tailings continuum in terms of the proportion of water or solids as (i) unthickened slurry, (ii) thickened slurry, (iii) thickened paste and (iv) filtered 'cake'. Common to the first three states in the continuum is that the tailings are in a fully saturated state and strength development depends on the rate at which water can be removed from the tailings. Tailings with high proportion of water pose operational, environmental, closure and safety risks due to large footprints required for storage, large volume of water to manage during operation, greater impacts when containment breach occurs etc.

Globally, over 95% of TSFs store tailings in the range of unthickened and thickened slurry tailings (<70% solids). As society continues to witness the risks associated with slurry tailings, the industry will continue to be under pressure to find alternative tailings management methods like filtration.

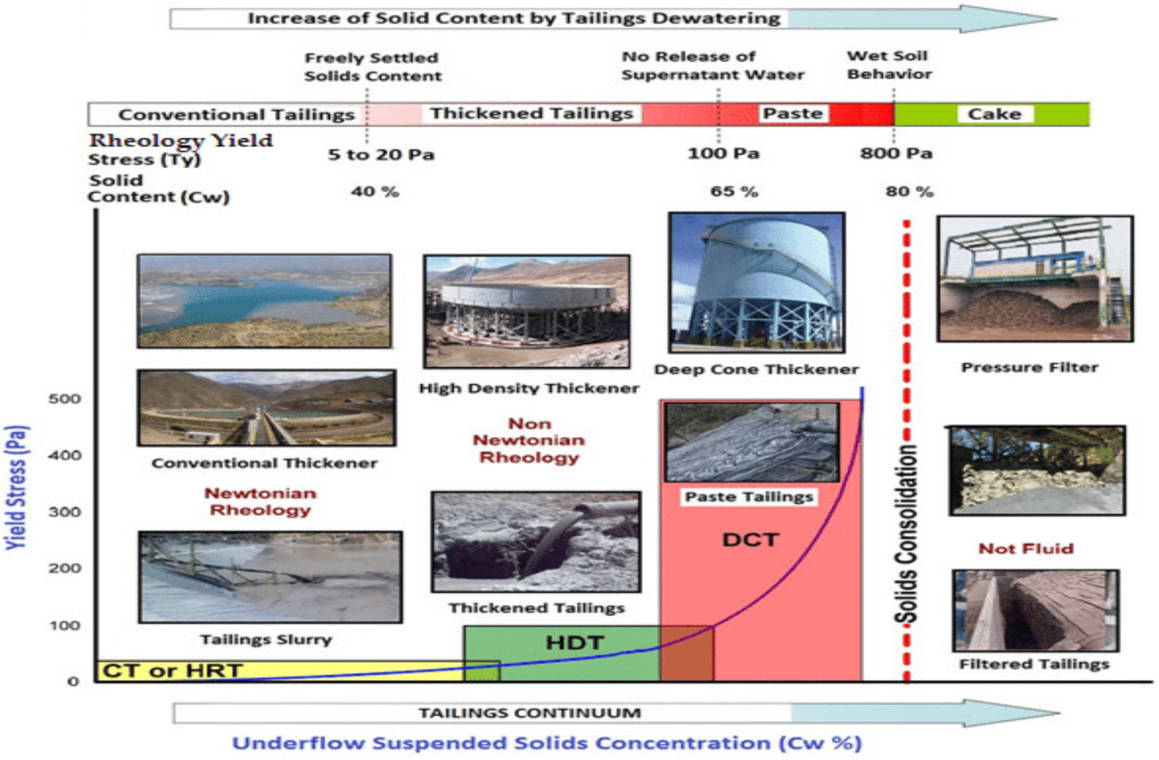


Figure 1 The tailings continuum (Cacciuttolo & Marinovic 2022)

2 Filtered tailings

2.1 Recent trends

Established theories and operational experience show that, under suitable conditions, storing tailings in a partially saturated or unsaturated state, commonly termed 'dry stacking', provide numerous benefits over conventional slurry tailings. To date, tailings filtration and stacking have mainly been adopted for harsh climatic conditions, such as very dry areas where water is a major constraint or in very cold conditions where water handling is difficult. Filtration has also been adopted in operations where process flow sheet dictates its use. Davies (2011) noted that two most common reasons to select dry stacked filtered tailings have been to recover process water and where terrain/foundation conditions restrict conventional impoundments.

Crystal et al. (2018) conducted an inventory of fully operating dry stack facilities across the world and noted that only two operations have capacities above 15,000 t/day, with only Karara operating above 30,000 t/day, although some new projects are considering filtered tailings capacities above 100,000 t/day.

Tailings filtration and stacking have traditionally been dismissed based on high costs (capital and operating costs), usually without consideration of lifecycle costs and risks. Technological constraints have also been a factor for high throughput operations where the unreliability of filtration equipment posed operational risks.

Recent tragic TSF failures are making it difficult to justify tailings risks by conventional cost/benefit analyses and some regulatory jurisdictions have moved to mandate tailings filtration and stacking regardless of cost. The significant advancement in filtration technology in the last decade has also made available more reliable filtration equipment suitable for high throughput operations, and improved material handling equipment provides flexibility to stack filtered tailings in different geometries. These have strengthened the case for filtered tailings to establish a place in the search for safe and sustainable tailings management.

2.2 Conceptualisation of filtered tailings storage continuum

Conceptually the filtered tailings storage continuum consists of (i) dewatering phases of thickening and filtration followed by (ii) material handling phases of conveying/transport, stacking/disposal, and (iii) storage facility operation. Figure 2 illustrates this conceptual continuum, which will be referenced in discussing the various stages of design and operation in this paper. Figure 3, (Metso, also in Cacciuttolo & Marinovic 2022) shows a schematic representation of the stages of tailings dewatering, and material conveying stages. The activities at each of these stages affect the others and therefore require close collaboration among the various teams involved.

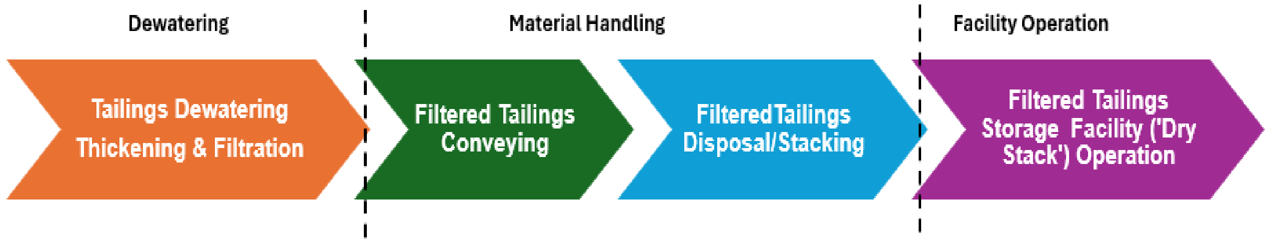


Figure 2 Conceptual filtered tailings storage continuum

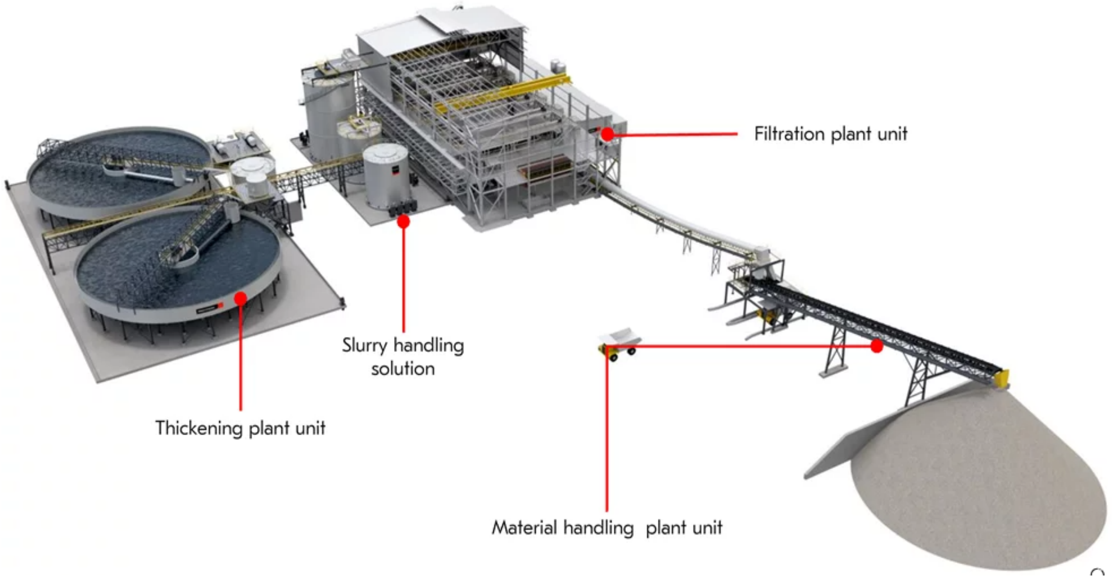


Figure 3 **Schematic representation of tailings dewatering and conveying/handling stages (Metso, Cacciuttolo & Marinovic 2022)**

3 Design considerations for filtered tailings

3.1 General design considerations

In general terms, design considerations for FTSFs are similar to conventional wet TSFs and involve evaluation of site-specific factors including topography, climatic conditions, drainage, locations in relation to processing plants, ground conditions, tailings materials characterisation, storage facility design, tailings handling and facility operation etc. However, conventional wet TSFs require an engineered containment embankment and relatively passive operational management practices. FTSFs are however, self-containing, sometimes requiring only a starter embankment to support conveying and stacking equipment but require active and intensive operational management practices.

Furthermore, unlike conventional tailings facilities where tailings density or solids content is normally specified by the processing plant design team for input into TSF design (usually without input from the TSF design provider), FTSF design requires inputs from providers involved in all stages of the filtered tailings storage continuum. Coordination between FTSF design, processing plant design, tailings dewatering (thickening and filtration) equipment designer/supplier, materials handling providers and facility operations team is required to ensure successful outcome. Performance criteria assigned by each of these groups tend to be different and sometimes conflicting, and therefore require collaboration from the early design stage. More importantly, filtered tailings moisture or solids content that will ensure successful material handling /disposal, and geotechnical performance of the facility in operation should be the key driver. The fundamental requirement for FTSF is that filtered tailings material at the time of deposition should be in a partially saturated or unsaturated state (defined by moisture content) and must be handled and operated to remain so during the life of the facility. This primary consideration should drive the selection and design of all dewatering (thickening and filtration), and handling/disposal equipment.

3.2 Considerations for tailings thickening

To reach an unsaturated state, the tailings dewatering process starts from thickening. The density and characteristics of tailings from the thickener presented for filtration have significant impact as they determine how much water will remain to be removed by the filters and influence the size and number of filters and filtration efficiency. Thickener capacity should be adequate to meet throughput and solids content requirements with due consideration of potential changes in the performance of upstream equipment and uncertainties in ore mineralogical characteristics. For example, design cycle times for the filtration equipment are based on a range of input densities/solids from the thickener, therefore densities outside the design range require changes in cycle time to achieve the desired moisture content of the filtered tailings. In general, tailings thickened to lower densities/solids content will require adjustment to cycle time to achieve the desired moisture. However, an optimum level exists whereby further increase in feed solid/density does not lead to improvement in cycle time, and this must be investigated during design.

3.3 Considerations for tailings filtration

Recent technological advancements in filtration have provided greater opportunities for a wide range of applications. Filtration options for dewatering tailings after thickening include vacuum filters, centrifuges, belt presses, and filter presses. The two main technologies widely used for industrial scale and high throughput filtration are the vacuum filtration (vacuum ceramic disc filters and vacuum belt filters) and pressure filtration (filter presses). If properly designed with consideration of material characteristics, both technologies can deliver satisfactory results. However, pressure filtration (filter press) appears to be more effective for large-scale operations with high throughputs and a wide range of material characteristics based on Karara operational experience and trials on other projects, although Davies (2011) and Hahn (2019) have both reported good performance of vacuum belt filtration for large operations. Vacuum ceramic disc filters are also currently being used in relatively large-scale tailings applications with satisfactory performance.

However, the filter type adopted, and its ancillary equipment should be engineered to meet the material characteristics, including solution chemistry. The tailings properties including particle size distribution and specific gravity have major influence on filtered tailings moisture. In the last decades, filter manufacturers have recognised the mining application and very high-capacity filters have emerged in recent years, with major improvements in filter component design. Figures 4a, b and c show different types of filters including the filter press used in the Karara operation (the details of which are found in Amoah 2019). It is important to emphasise that different filter types have different efficiencies for the desired moisture content, throughput, and operational reliability requirements and this should be carefully investigated during design.


(a) (b) (c)

Figure 4 Typical filtration equipment used for large-scale tailings application. (a) Vertical plate filter (filter press); (b) Vacuum ceramic disc filter; (c) Vacuum belt filter

3.3.1 Considerations for design of filter press equipment

Several filter types are available in the market for a wide range of tailings application, but the guiding principle for tailings filtration is to design the filter equipment that will achieve the required filtered tailings quantity (throughput) at acceptable moisture content and required level of availability. The information discussed here may have general application but is presented in the context of the filter press used in the Karara operation. Factors for consideration in design include:

- Filter component design consistent with tailings material characteristics
- Filtration moisture content achievable by the filter

- Design production rate (design cycle times and number of cycles per day)
- Filter equipment reliability (proper estimate of percent run times, unplanned downtimes)
- Level of automation and operational flexibility
- Input factors such as feed densities
- Ancillary and auxiliary equipment design consistent with filter design criteria
- Robustness of design to operate in harsh conditions.

These factors affect design in terms of number and size of filters, filter clothes, plates, and component parts.

3.3.2 Filter press component design

Filter press component design should carefully consider the different factors that affect filter operational efficiency. The key components of filter press are the frame, filter plates, manifold (piping and valves), and filter cloth. The performance of each or combination determines the efficiency of the filter press in operation. Each component should be engineered to suit throughput, and tailings characteristics, (e.g. gradation, mineralogy) that affect the performance of other components parts such as filter cloth.

The size and number of filters adopted should consider the engineering and operational factors, such as intensive maintenance requirements that will affect overall filter availability. Key factors such as level of automation, operating conditions in terms of chemical and thermal, mechanical factors such as filter pressing pressures, material particle hardness and abrasive properties etc. are major considerations.

3.3.3 Filter cloth

Filter cloth is one of the most critical components of the filtration equipment that affects availability and filtration efficiency. Key considerations for filter cloth include resistance to blinding, ease of filter cake discharge, solution chemistry, wear and tear resistance, etc. The performance of filter cloth affects the moisture content for a given cycle time and filter availability in terms of frequency of cloth change.

Different types of filter cloths have significantly varying performance under the same operating conditions in terms of the number of cycles achieved before cloth changes are required, and these can vary from 3,000 to 5,000 cycles (for typical filter press operation). Good cloth performance results in lower cycle times, higher number of cycles per day and high production levels, while the converse is also true. Achieving high number of cycles before cloth change means less cloth related downtime and high availability.

An extensive evaluation of filter cloths in the market should be undertaken for particle gradation around the clay/silt size fraction, solution chemistry, abrasiveness, and tailings densities during the feasibility study. Filter cloth review should also be done on a continuous basis during operation by testing different cloths on different filters within the cluster under the same operating conditions and measuring performance in terms of cycle times to achieve desired moisture, and number of cycles before cloth repair or change is needed.

3.3.4 Filter cycle times

The cycle time and number of cycles achieved determine the quantity of tailings filtered per day. Filter cycle time adopted in design also determine the number and/or sizes of the filters to achieve desired moisture content for the required throughput. However, several factors affect the cycle time including the feed characteristics such as density, particles size/minerology, feed pressures, quality and age of the filter cloth and operational factors like plant maintenance. For example, low feed density will require a longer cycle time to achieve the desired moisture content and high feed density leads to lower cycle time, but an optimal feed density exists beyond which an increase in solids content has minimal effect. Therefore, design cycle time must be set to optimise target production and moisture content requirements.

In practice, the cycle time achieved and hence, the number of cycles per day, varies for each filter even under the same operating conditions. Figure 5 (Amoah 2019) shows typical daily cycles achieved over a month.

An average of 115 cycles/day was achieved versus a design average of 130 cycles per day. The number and sizes of filters in relation to cycle times should take into consideration uncertainties in the influencing factors to ensure plant throughput is achieved. Adequate design investigation must be undertaken to ensure appropriate levels of redundancies are built into the design to deal with input uncertainties and changes.

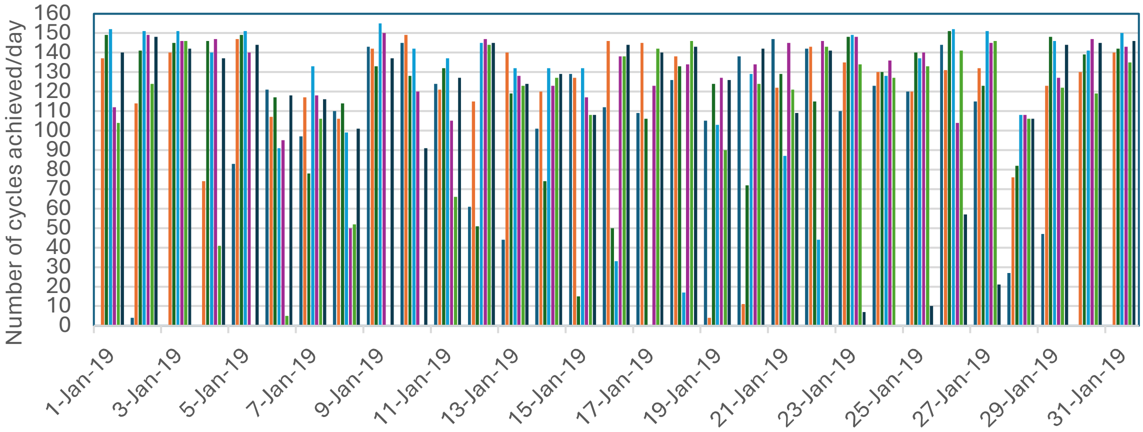


Figure 5 Example of number of cycles achieved for typical filter press in operation (Amoah 2019)

3.3.5 Ancillary equipment

The filtration plant operates as a unit; therefore, the main equipment component design should be done in conjunction with the ancillary equipment design. For example, the performance of the filter in terms of design cycle time can be affected by the feed pressure to achieve target moisture. Therefore, the ancillary equipment, such as the filter feed pumps, must be capable of achieving the required feeding pressure into the filter presses. At the same time, the filter presses must be able to withstand the feeding pressure. Where ancillary equipment manufacturer differs from filter manufacturer, adequate design coordination is required.

3.3.6 Filter availability and production rate

Filter availability depends on the performance of the filter components and ancillary equipment. As with all mechanical equipment, a good asset management and maintenance plan should be implemented to ensure that preventative maintenance is regularly undertaken, and critical spares are readily available to minimise excessive unplanned downtimes. Figure 6 shows typical filter availability measured by percent run times for each cluster of filters. Filter design availability (average) is 83% (required), versus an average of 75% achieved across all filters.

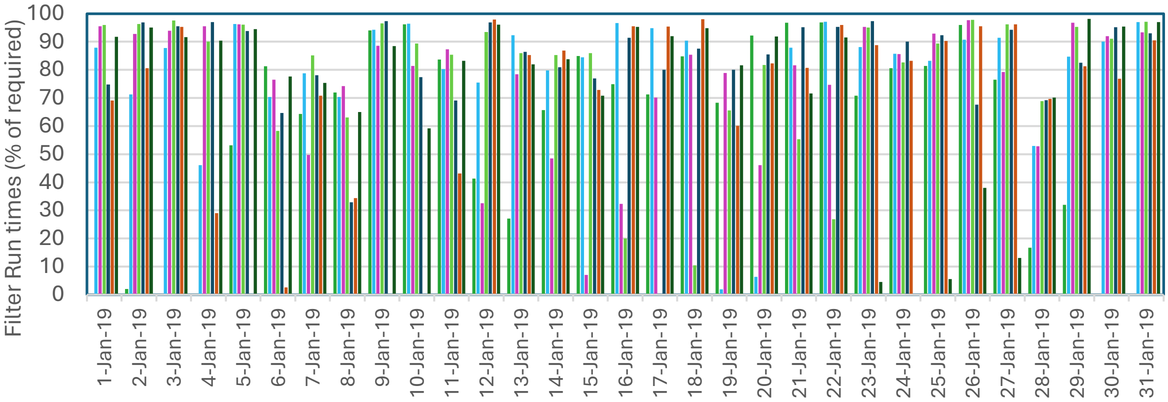


Figure 6 Example of filter run times for typical operation (Amoah 2019)

Significant variations exist between the different filters in their availability. A reasonable balance between maintenance and availability across multiple filters is critical for compensating for unplanned down times. Filter production rate to meet design throughput depends on cycle times achieved and availability based on unplanned downtimes. Figure 7 shows filter production rate for the Karara operation (modified from Amoah 2019). Filter design should consider the high maintenance demand and potential unplanned downtimes to build adequate redundancies in the number and sizes of filters to ensure design production rates.

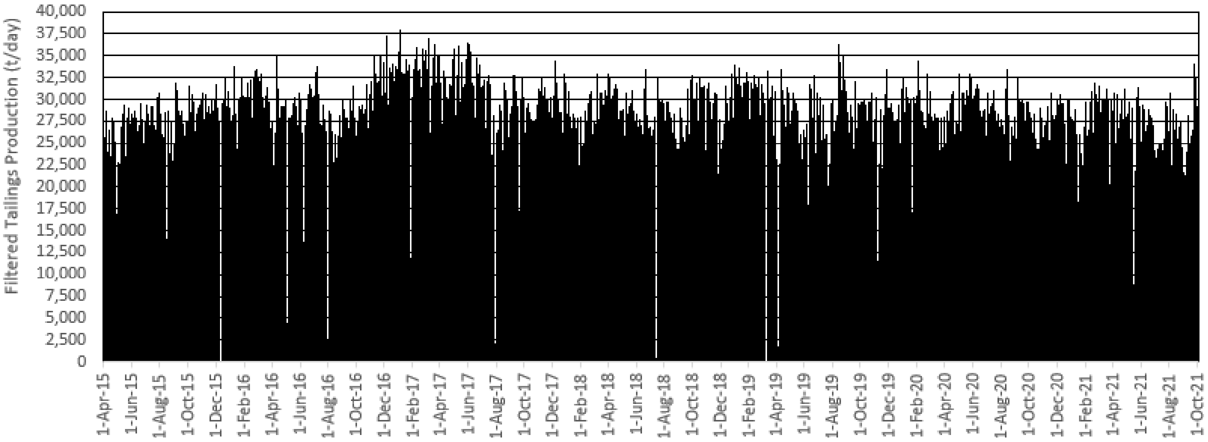


Figure 7 Typical daily filtration rate

3.4 Filtered tailings moisture contents

The filtered tailings moisture content achieved is the most critical success factor for the entire filtered tailings operation. The target gravimetric moisture content, expressed in geotechnical engineering terms as the ratio of mass of water to mass of solids (M_w / M_s), should be agreed with the design teams in other disciplines.

The target moisture content and its range of acceptable variations that will achieve an unsaturated state of the filtered tailings must be the critical parameter driving the design of the dewatering equipment (thickening and filtration equipment) and the development of an operational monitoring system. The starting point in the design consideration is to identify the tailings moisture contents at critical engineering behaviour points such as Atterberg limits (e.g. liquid limits and plastic limits), standard Proctor optimum etc., to predict the potential behaviour of the filtered tailings during transport, stacking or disposal and facility operation. Several factors cause variations in tailings moisture during filtration, some of which include the following:

- Changes in ore characteristics that affect the thickening and filtration process and hence, the moisture contents achieved at a given design cycle time.
- Performance of upstream equipment that affects gradation and hence thickening efficiency which further influences tailings thickened density presented for filtration.
- Filter performance due to pressing pressure, cycle times, filter cloth age and effectiveness.
- Variations in filtered tailings moisture due to operator experience and operating discipline.

Current technology has advanced to the stage where available filtration equipment can filter to very low moisture contents (below the standard optimum moisture content). However, operational experience from Amoah et al. (2018) shows the moisture content of the filtered tailings measured prior to deposition in the FTSF varies significantly (Figure 8 - BIS). Moisture variation should be considered as an integral part of tailings filtration; therefore, a target moisture content is only the starting point for determining performance criteria.

The driving criteria should be a target moisture content and acceptable range of moisture variation that will provide an optimal balance between dewatering equipment design and geotechnical requirements for FTSF in operation. This is crucial for setting proper performance measures for the dewatering equipment (filters and thickeners) and requires close collaboration with filter equipment manufacturers, material handling and disposal service providers, process facility design and FTSF designer. Every effort should be made to ensure a sensible balance between filtration cost, output, engineering performance, and operational effectiveness, without compromising the geotechnical requirements for the filtered tailings in the storage facility.

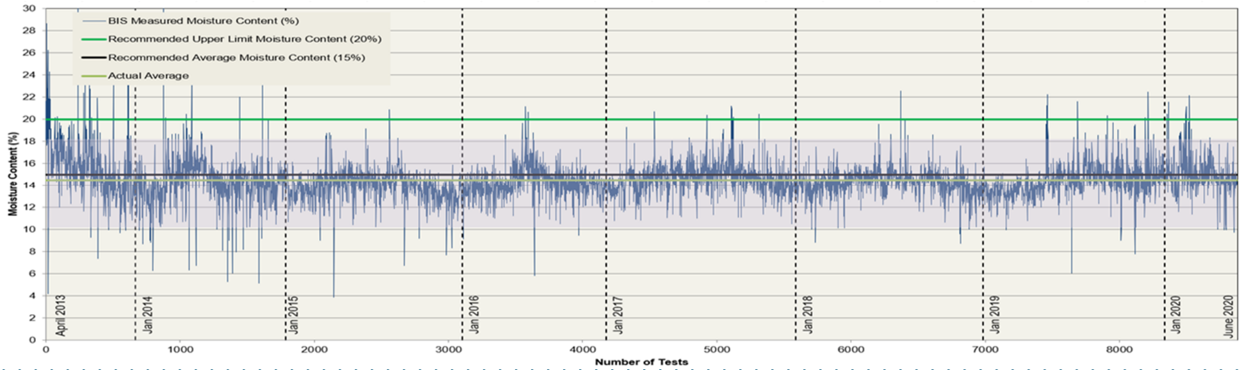


Figure 8 Filtered tailings moisture content (modified from Amoah 2019)

4 Filtered tailings handling

4.1 Design considerations for tailings transport/conveying system

The two main methods of transport and disposal are trucking and mechanical conveying and stacking. The selection of filtered tailings transport and disposal method depends on several factors, including the tailings quantities, conveying distance, size of the FTSF, topography, and other local factors that dictate the economics of the operation including life of mine. However, any material handling and disposal system adopted should take into consideration the requirements for tailings variability, production rates, long-term production targets and other operational factors that can create the need for emergency handling.

Analyses of tailings disposal options at the early stages of the Karara operation indicated that trucking option is more cost-effective for smaller throughput operations less than 15,000 t/day and mine life under 15 years. For such small operations, the size of the trucking fleet required, and the relatively small size of the facility make it economical to manage and respond to upset conditions. For large throughput operations, trucking option becomes inefficient and uneconomical, especially when production levels exceed 20,000 t/day due to the size of the fleet required and as the size of the FTSF increases. The capital, planning and operational maintenance of the loading and trucking fleet required for large operations approach that of a medium size open pit mining fleet. Another major limitation of trucking is trafficability on haul roads and on top of FTSF during wet weather conditions and when tailings moistures are higher than design.

For high throughput operations, mechanical conveying and stacking are more economical and operationally efficient and allows operational control of the stacking/disposal of large volume of material throughout the year with minimal limitations of trafficability. A mobile conveyor system consisting of moveable sections and a detachable stacking system offers an efficient way of transferring and depositing the filtered tailings in a planned, controlled, and progressive manner.

However, even with a fully mechanised tailings handling approach, operational issues will require trucking to be an integral part of the FTSF operation. Equipment planned and unplanned downtimes, changes in tailings moisture, conveyor extension etc. will create a need for emergency handling using a small fleet of trucks.

4.2 Design considerations for tailings stacking/disposal

Mechanical disposal/stacking approach provides a more efficient method for managing and controlling the tailings placement process within the facility. The mechanical stacking system should be built on tracks to move over difficult terrains and harsh surface conditions. The two common methods of mechanical stacking are the advancing and retreating methods, and the choice depends on stacking geometry and/or space.

The retreating method stacks the material from ground level, usually to heights under 10 m and is better suited for stacking in strips (Figure 9a). Where stacking geometry is to optimise space, a combination of radial and strip placement offers the best approach using the radial advancing stacking system.

The tracked radial stacking and advancing method adopted for Karara operation (Figure 9b) stacks tailings from heights up to 30 m (lift height). The system can self-drive over difficult ground conditions (Figure 10), has excellent manoeuvrability with complete rotation, and can control discharge heights and distances.

The equipment system is designed in modular sections such that the mobile conveyor is easily moveable and detachable for operational flexibility to either place the tailings in parallel strips or in radial arc as required by the stacking design geometry to optimise FTSF space. Normally, stacking height is dictated by the tailings moisture contents and climatic conditions that determine the angle of repose and stability of outer slopes.

(a) (b)

Figure 9 Mechanical stacking methods. (a) Filtered tailings stacking by retreating method; (b) Filtered tailings stacking by radial advancing method

Some key design considerations for mechanical stacking to ensure efficiency include the following:

- The stacker should have capacity for the design stacking rate and throughput with maximum reliability, therefore stacking equipment design should have redundancy built into it.
- Stacking equipment design (including component parts design) should be mechanically robust to withstand harsh operating conditions. Equipment should handle weight, abrasiveness, material chemistry, extreme weather conditions and difficult surface conditions shown in Figure 10.
- The stacker unit, including the conveyor, must be designed to have maximum mobility and flexibility to move from one location to another without too much difficulties.
- Stacking equipment system must be designed for easy of operation to achieve high availability and utilisation rates (minimising unplanned downtimes).
- A high level of automation to maintain accuracy of deposition, with allowance for operator control.
- Minimise planned downtimes during system changeovers and re-assembly at the end of designed deposition cycle (sweep or lift).
- Equipment should operate and stack tailings to meet geotechnical requirements, e.g. flexibility of changing equipment setback distances during upset conditions without compromising stacking rates.
- Operational safety control systems, e.g. emergency stops, safety guards, warning alarms etc.

Figure 10 Mechanical stacking equipment operating in upset condition – high moisture tailings

4.3 Consideration for temporary storage and emergency handling

The design of the material handling and disposal system should make an allowance for a temporary transfer and storage area to handle upset conditions that prevent disposal/stacking or in case of an unplanned down time of stacking equipment. The temporary transfer area should be designed to accommodate a minimum three days of production (unless otherwise dictated by operational risk appetite of the facility owner) from which the materials can be stored and trucked to a dedicated area in the FTSF. An emergency storage and handling area (Figures 11a and b) should therefore be an integral part of the FTSF operations plan.

(a) (b)

Figure 11 Emergency storage and handling. (a) Emergency storage; (b) Emergency handling by trucks

5 Filtered tailings engineering properties

5.1 Characterisation of saturated and unsaturated properties

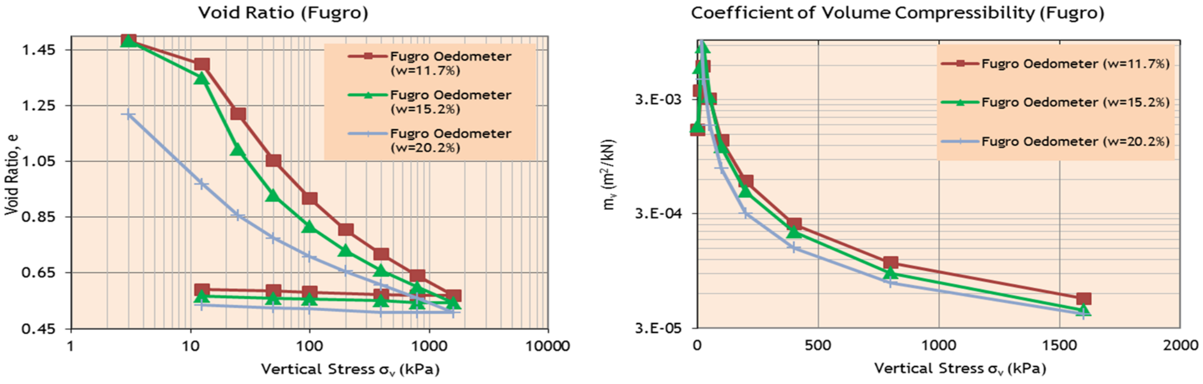
The engineering behaviour of the filtered tailings should be evaluated for saturated and unsaturated states. The primary focus is on the hydraulic, shear strength and deformation properties that determine the performance of the tailings in situ etc. Tests on saturated material for shear strength, compressibility, and hydraulic properties provide a baseline or reference point for understanding the differences that occur under unsaturated state. Moreover, filtered tailings can exist in both saturated and unsaturated states due to upsets in operation and changes in in situ conditions.

Filtered tailings characterisation covers all the standard tests undertaken for conventional wet TSF containment design. These include classification tests for index properties, shear strength, hydraulic conductivity, moisture–strength relationships obtained through Proctor compaction tests and consolidation/deformation tests for compressibility. The tests should cover sample minerology, moisture contents, and magnitude of stresses anticipated for the FTSF life.

5.1.1 *Consolidation settlement test*

The purpose of the consolidation settlement test is to simulate the compressibility behaviour of the material at high deposition thickness as a function of changes in tailings moisture content. Figure 11 show the tailings deformation characteristics obtained from an oedometer test (one-dimensional consolidation test) within a stress range to 1,600 kPa and at different moisture contents for magnetite tailings (with specific gravity 3.0) at the Karara operation. The three test moistures were selected to represent critical engineering behaviour points of the tailings (liquid limit = 25, plastic limit = 18, standard Proctor optimum moisture 14–15% etc.).

Figure 12a shows the relationship between applied stress and void ratio in typical compression and swelling plots for the three different moisture contents, and Figure 12b shows the applied stress and coefficient of volume compressibility (m_v) relationship. The results show that filtered tailings moisture content directly influences void ratio and compressibility behaviour, with higher moistures resulting in higher compressibility. Understanding of tailings compressibility behaviour is important especially as the tailings placement is done in very thick lifts up to 30 m.

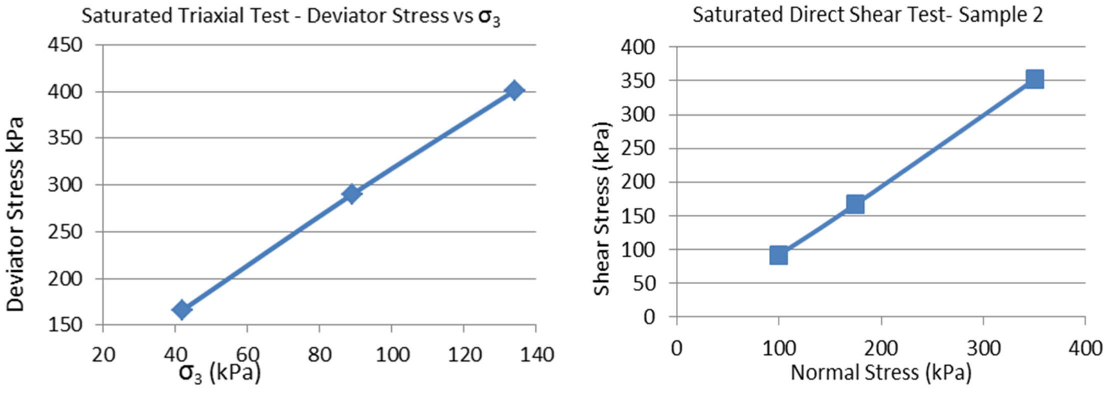


(a) (b)

Figure 12 Results of one-dimensional consolidation settlement test. (a) Compression and swelling plot – vertical stress versus void ratio; (b) Vertical versus coefficient of volume compressibility

5.1.2 *Saturated shear strength properties*

Shear strength behaviour was investigated by single stage direct shear and multistage triaxial tests on saturated tailings samples (reconstituted samples) undertaken to assess shear stress responses. Results of both triaxial and direct shear tests are shown in Figure 13 and indicate linear response to the stress state variable (normal stress) under a given confining stress (100 kPa). These saturated tests provide a useful reference for comparison with unsaturated tests and the behaviour under the different state variables.



(a) (b)

Figure 13 Shear strength response to applied stress. (a) Triaxial test; (b) Direct shear test

5.2 Unsaturated properties of tailings

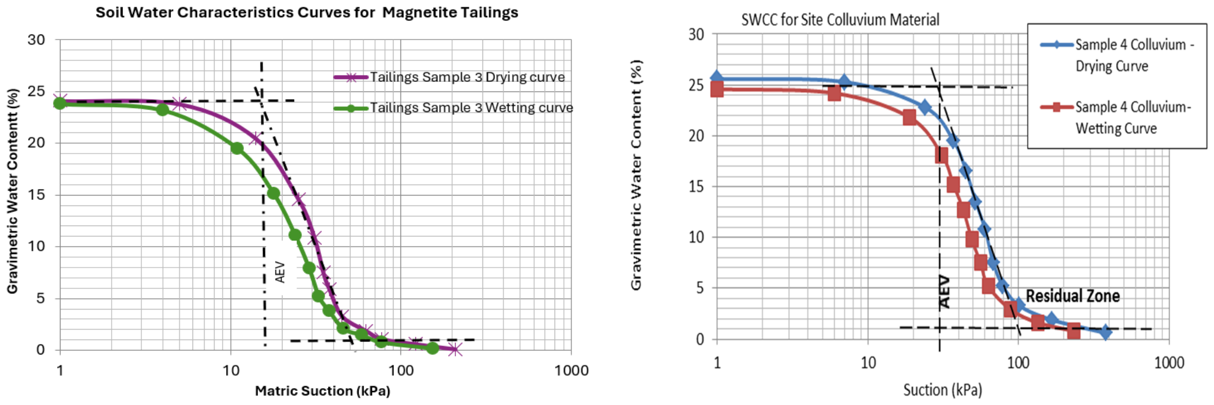
Filtered tailings have the primary requirement for being in unsaturated state during their lifecycle, therefore investigating the properties at this state is very important for developing the control processes in the various stages of the tailings storage continuum, from design through to operation. Saturated soils exist as two-phase material, water–solid system where all void spaces between the solids are filled with water (S=100%, S is degree of saturation). Partially saturated or unsaturated soils exist as multiphase material, air–water–solid system whereby the voids spaces between the solids are filled with air and water (0<S<100). Completely dry soils exhibit the direct opposite of saturated soils, where all void spaces are filled with air (S=0). The engineering properties of the tailings at these states differ and highly influence the hydraulic and shear strength behaviours.

5.2.1 Hydraulic properties of unsaturated tailings

When soil is in a partially saturated or unsaturated state, the hydraulic properties depend on the degree of saturation (S). Application of matric suction results in water loss in soil (drying) and entry of air into pore spaces. These are accompanied by changes in soil volume, degree of saturation, hydraulic conductivity, void ratio, and shear strength. Changes in the degree of saturation have the most significant effect on hydraulic conductivity as the void spaces now occupied by air need to be displaced before water can move through.

The relationship between matric suction and soil moisture changes is expressed as soil water characteristics curve (SWCC) and is commonly used in soil science and engineering disciplines when assessing soil water storage behaviour during wetting and drying cycles. These behaviours differ from soil to soil and must be investigated to understand the unique characteristics of the in situ tailings material.

An important parameter obtained from SWCC curve is the air entry value (AEV), which represents the matric suction beyond which air starts to enter a saturated soil and therefore, marks the transition from saturated to unsaturated soil. Figure 14 shows a sample of SWCCs for magnetite tailings and the foundation material (predominantly colluvium). The AEVs are different for the two soils and indicate that the water retention, saturation, and desaturation characteristics will also be different under the same conditions. For example, the tailings material has AEV around 18 kPa while the colluvium has AEV around 30 kPa therefore, the tailings material will desaturate sooner than the colluvium under the same matric suction or summer conditions.

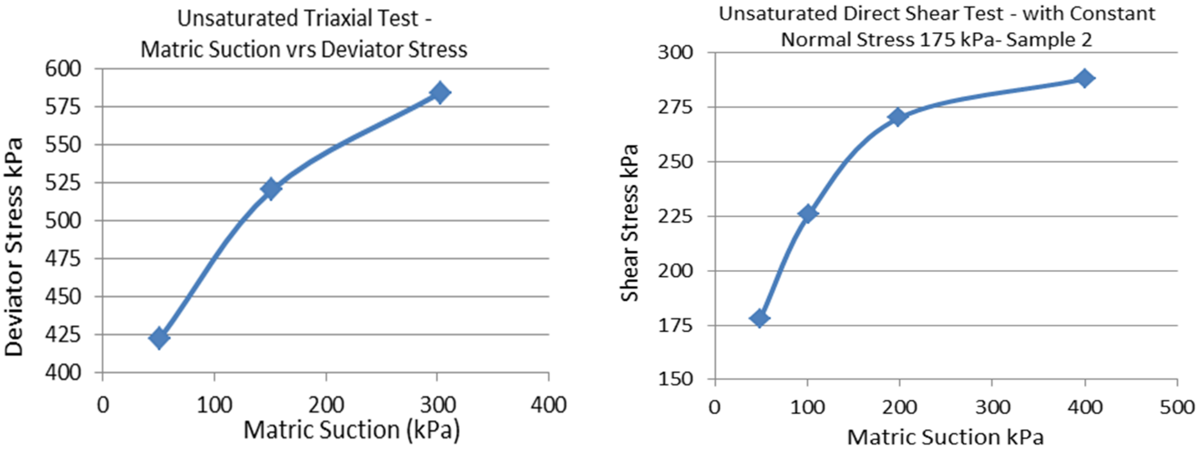


(a) (b)

Figure 14 Soil water characteristics curves. (a) Magnetite tailings; (b) Overburden colluvium material

5.2.2 Unsaturated shear strength properties

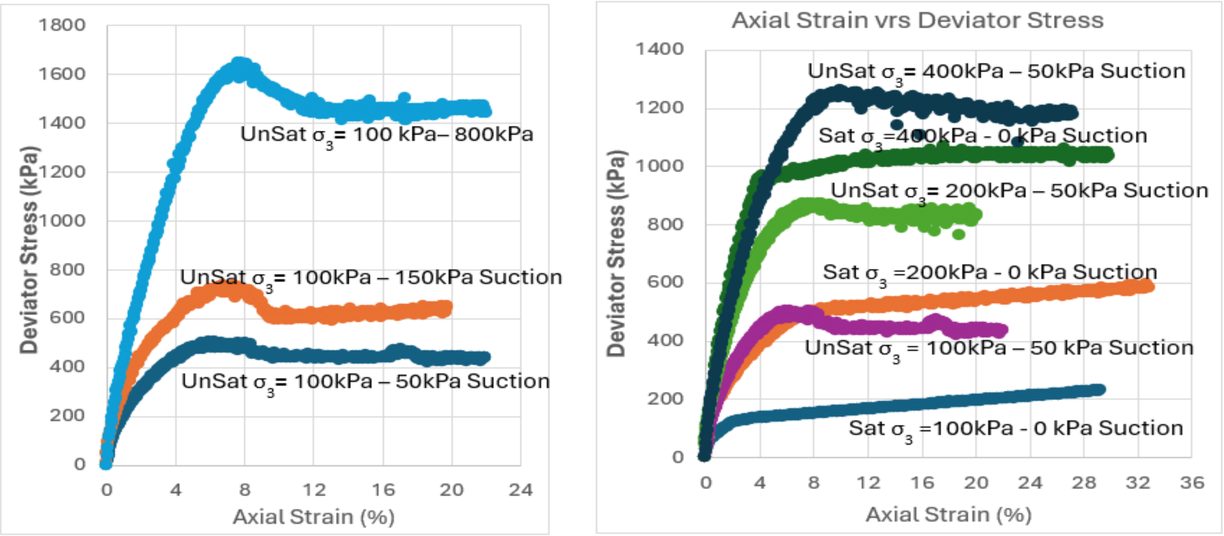
Unsaturated soils are subjected to two stress state variables (Fredlund & Rahardjo 1993), net normal stress and matric suction, and these work in combination to determine the shear strength of the soils. Unsaturated tests provide a good understanding of the shear strength responses to the range of matric suctions associated with the climatic conditions of the FTSF location. Figure 15 (Amoah et al. 2018) shows the shear strength responses over a range of matric suctions (50 to 300 kPa) for magnetite tailings. The measured shear strengths increase with matric suction (stress state variable) and exhibit nonlinear relation, which is different from the linear relations observed for saturated tests in Figure 13.



(a) (b)

Figure 15 Shear strength response to matric suction (Amoah et al. 2018). (a) Triaxial tests; (b) Direct shear

The effect of matric suction is further demonstrated in Figure 16a which shows the variation of shear strength with suction for confining stress of 100 kPa and Figure 16b showing tests with net confining stresses between 100 and 400 kPa, and a range of matric suctions between 0 (saturated) and 400 kPa. The test results again provide interesting insights into the behaviour of the filtered tailings under saturated and unsaturated states. With the application of matric suction, the deviator stress quickly reaches peak strength and then remains constant when axial strains exceed 12%, exhibiting no significant changes in stress. For the tailings in a saturated state (0 kPa suction), changes in deviator stress still occur (still increasing) even at large axial strains above 25%. The effect of matric suction (by increasing shear strength of the filtered tailings in situ) is demonstrated by the higher-than-expected steep angles (around 44°) achieved at Karara site (Amoah et al. 2018).



(a) (b)

Figure 16 Plot of axial strain versus deviator stress. (a) Shear strength response to matric suction at given confining stress (100 kPa); (b) Shear strength response to different matric suctions (0 kPa suction and 50 kPa suction) an different confining stresses

6 Operational considerations for filtered tailings storage facilities

6.1 Water management considerations

Water management considerations for FTSFs are equally important as with conventional wet TSFs in terms of catchment area surface water runoff and facility surface water control.

6.1.1 Facility catchment area water control

The siting of FTSF facility should take into consideration the presence of stream beds and drainage channels, and wherever possible, these should be avoided. Where this is not possible, drainage control involving the design and construction of surface water diversion channels to ensure that the facility is isolated from large surface runoff water should be installed. Diversion channels should be designed for the site rainfall risks and integrated with environmental control requirements to minimise surface water impact. Ponding within the local catchment in the immediate vicinity of the FTSF should be avoided to protect the toe of the active dry stack by installing toe drains and/or levee banks.

6.1.2 Facility surface water ponding control

FTSFs are not water storage structures, and therefore water ponding on the facility surface should be controlled to (i) minimise infiltration and (ii) avoid erosion and piping holes through cracks. In general, FTSFs should not be allowed to store surface water or have surface ponding over a long period. Understanding the water storage and retention characteristics of the tailings material from the SWCC will provide good guidance into the effect of surface water ponding and the extent of management controls required.

The risk of surface water ponding on the FTSF depends on the climatic conditions. In dry areas such as in Karara operation, the effect of surface water ponding and infiltration is minimal as the long dry summers help to maintain unsaturated state (Amoah et al. 2018). However, controlling surface water is critical in net positive rainfall areas to minimise infiltration and to prevent tailings from changing from unsaturated to saturated state. Tailings compaction is a good and common practice to increase in-situ strength, reduce the hydraulic conductivity, and minimise infiltration rate, but this should be combined with surface grading to facilitate water runoff to achieve effective and reliable control. Surface grading should minimise concentrated flows and erosion by limiting the gradients, flow lengths and be integrated with the facility earthworks program.

Surface water control and water ponding at the edges must be controlled even in dry climates. Water through crack holes creates piping holes may open at the outer surface (Figures 17a, b) to create local slope instability as was experienced at early stages of the Karara operation until control measures were established.

(a) (b)

Figure 17 Effects of surface water ponding and infiltration. (a) Sinkholes developing due to infiltration through surface cracks; (b) Piping hole opening at outer face of dry stack embankment

6.2 Filtered tailings moisture monitoring

Tailings moisture content at the time of disposal is very critical for the operational performance of the facility. A strict monitoring program for tailings moisture at the filtration plant (production end) and at the disposal facility (disposal end), including visual observation and laboratory testing, should be established as an integral part of FTSF operation. A minimum of two tests per shift (at each end) should be undertaken and recorded for reporting. Visual inspections during conveying to the stacker is a critical final monitoring point to prevent placement of higher than desired moisture in the facility (Figure 18a). A response plan to promptly deal with such upset conditions should be established with clear reporting lines.

Changes in filtered tailings moisture will occur periodically due to ore characteristics and/or efficiency of dewatering equipment and will require prompt operational response to avoid material handling problems. Figure 18a (also shown in Figure 10), illustrates typical upset condition due to high moisture content and its effect on stacking operation compared with Figure 18b (tailings with right moisture content), therefore monitoring is crucial to detect upset conditions earlier and activate emergency handling and storage.

(a) (b)

Figure 18 Effect of moisture content on stacking operation. (a) Higher than design moisture (upset conditions); (b) Design moisture content (normal condition)

6.3 Asset management and maintenance planning for FTSF

FTSF operation is equipment-intensive (Figure 19) and therefore good maintenance, and asset management planning for the operation is critical. An inspection plan, condition monitoring and maintenance regime that ensures early problem detection, system reliability and high availability should be established and managed in the same manner as in the processing facility or any major equipment-intensive operation.

Figure 19 Mechanical conveying and stacking equipment for FTSF (equipment-intensive operation)

Key operational rules for effective FTSF operation include the following:

- FTSF operation should have a rigorous preventative maintenance program to ensure operational reliability, equipment availability and high utilisation.
- The monitoring and maintenance processes and procedures should be robust enough to detect likelihood of component or system failure, identify failure modes, improve early system failure mitigation, and provide accurate system condition responses.

- A robust inventory management system should be established to ensure the identification and availability of critical spares and rapid response to unusual equipment/material demand situations.
- The overall asset management program should be able to respond to an expanding plant as FTSF size increases and with changing conditions of plant with age (proactive and long term planning).
- Operating discipline involving proper operation, adherence to planned maintenance, operator experience, prompt reporting, availability of critical spares, general inventory management etc.
- Conveyor extension at the end of the deposition cycle requires adequate planning and procurement of long lead items to minimise down times between deposition cycles.
- An operations management plan that captures all key requirements to ensure system performance management shall be developed and reviewed periodically or at least twice a year.

7 Operational performance monitoring

Globally, FTSFs are limited in number and period of operation compared with conventional TSFs, therefore, many questions about their in-situ performance will remain unanswered for some time. This section provides some useful insights obtained from observations and experience from the Karara operation on key areas, including (i) strength development within the in situ tailings (ii) moisture profile and changes compared with deposited moisture, (iii) water storage/retention behaviour such as phreatic surface, groundwater zones etc.

7.1 Shear strength performance monitoring

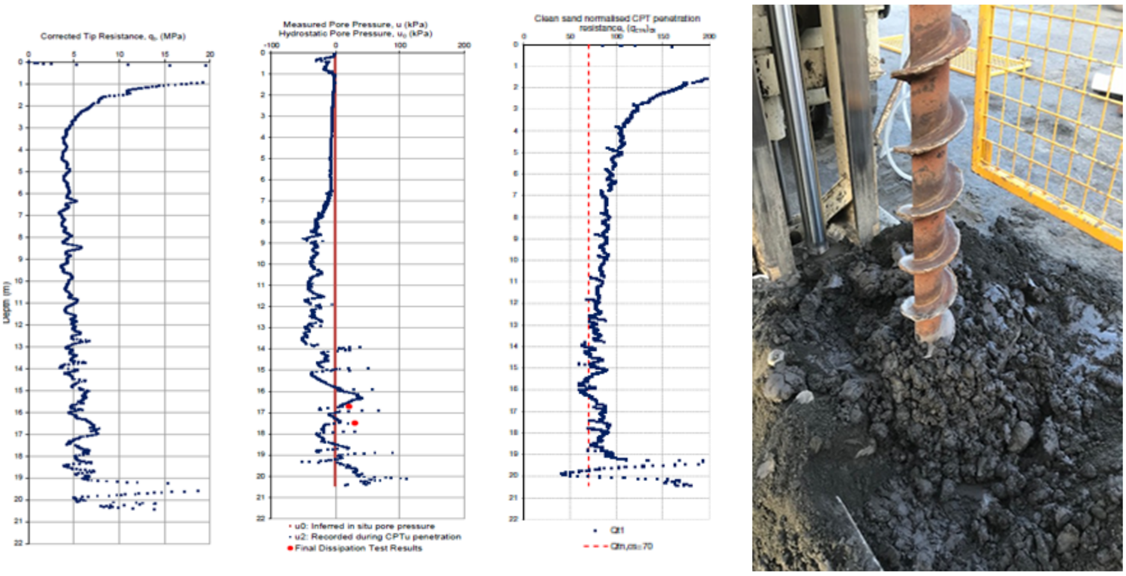
Shear strength performance in terms of strength development within the FTSF is important for assessing the stability of the structure. FTSF shear strength performance is assessed by in situ tests including (i) cone penetration tests (CPT) undertaken periodically and (ii) drilling to visually observe materials and collect samples for laboratory tests to supplement CPT tests. For the Karara operation, a program of annual CPT tests was established, and data were compiled to monitor strength development over the years. Annual CPT tests conducted over seven-year period show a consistent increase in in-situ strength (Figure 20a), where the tip resistance values for each year plot on the right side of the previous year's. Tests on tailings samples from depths between 5 and 20 m below surface had densities greater than 90% of standard maximum dry density.

(a) (b)

Figure 20 Strength development and material encountered at different location (DSP). (a) Cone penetration tests showing consistent increase in strength; (b) Unsaturated tailings material encountered at different locations and depths

7.2 Hydraulic performance: moisture profile within dry stack

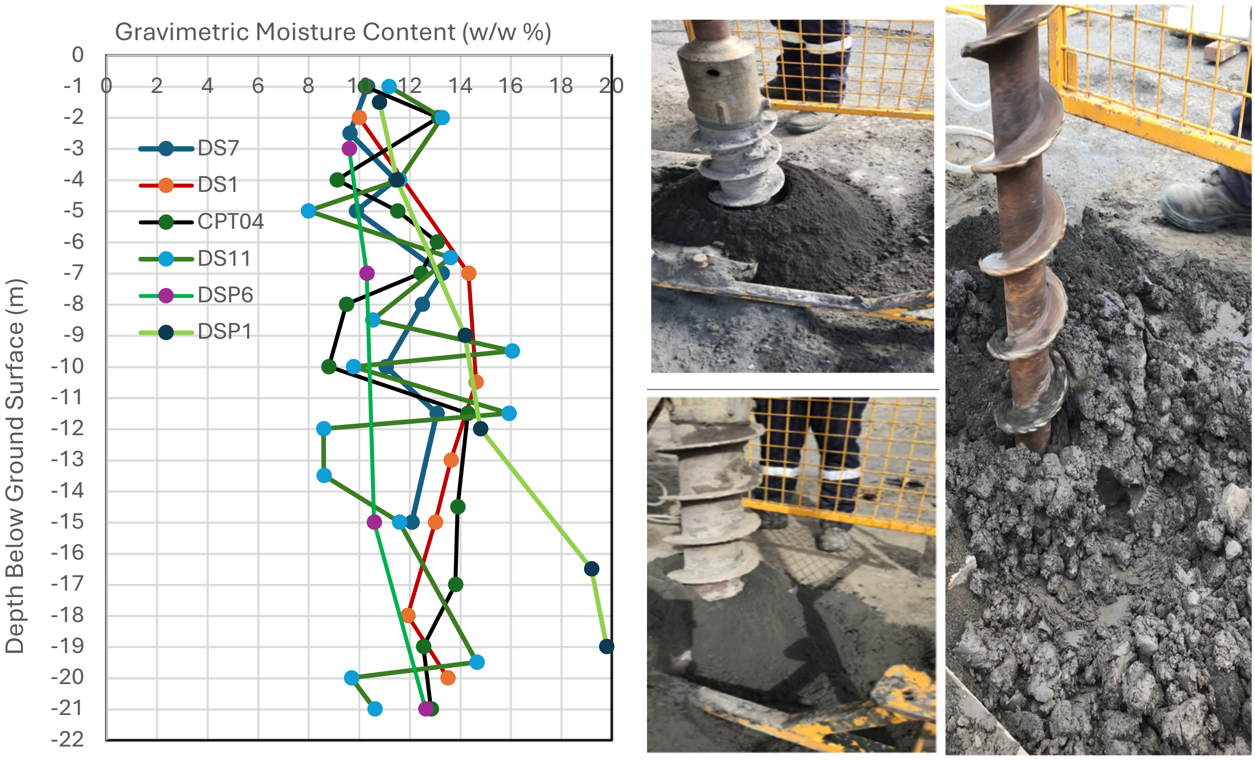
Hydraulic performance involves the understanding of the water storage and retention behaviour within the Dry stack in terms of general subsurface water movement, water table or phreatic surface (continuous or discrete groundwater zones), in situ tailings moisture content changes with depth etc. Drilling investigations at different locations to various depths provided insights into the moisture profile within the FTSF. CPT results were correlated with drilling results. In many locations, materials observed from drilling complemented CPT tests results in terms of zone/depths of negative pore pressure, as shown in Figure 20b. At locations where CPT results show positive pore pressures and high strength/densities (Figure 21a), drilling encountered similar materials at the same depth that were very stiff but at the same time were wet (Figure 21b).



(a) (b)

Figure 21 Correlating cone penetration tests (CPT) results with drilling investigations. (a) CPT tests showing zones of positive pressure; (b) Stiff and wet material encountered at drill depth where CPT test showed positive pore pressure

Figure 22a shows the moisture profile within the storage stack at different locations representing different years of deposition. Moisture contents mostly vary between 9 and 15% and are mostly within the moisture range deposited (12 to 18%, see Figure 8). No consistent trend in moisture variation with depth is observed, and the material remains in an unsaturated state. In areas (e.g. location DSP1, Figure 22a) where tailings with higher moisture were deposited historically (see Figure 18), materials encountered at the upper 12 m had low moisture similar to other areas (slightly moist to dry). However, at depths below 14 m, moisture contents were very high, similar to that at the time of deposition (around 20% w/w). This was consistently encountered in three locations where historically wet materials had been placed. Groundwater zones were encountered at discrete locations and depths and no continuous water table (phreatic surface) was encountered.



(a) (b) (c)

Figure 22 **(a) Moisture profile in dry stack; (b) Unsaturated material at 19 m depth in locations with historically low moisture tailings; (c) Wet tailings at 19 m depth in a location with historically high moisture tailings (DSP1)**

8 Operational costs for filtered tailings storage facility

The components of FTSF operation costs may depend on the method of cost allocation in the organisation. Some organisations may include cost for conveyor extension in operations costs, while others may only include day-to-day operation and equipment replacement costs. For Karara operation, operational cost for disposal includes conveyor extensions costs and the components reported by Amoah (2019), were:

- Filtration cost: all costs for operation and maintenance of filtration facility and immediate conveyor
- Filtered tailings disposal cost: all costs associated with the day-to-day operation and maintenance of FTSF, and all costs associated with installation of conveyor extension after each deposition cycle.

The historical unit costs for filtration and filtered tailings disposal are shown in Figure 23. It must be noted that the unit costs are sensitive to production levels and lower production results in higher unit cost.

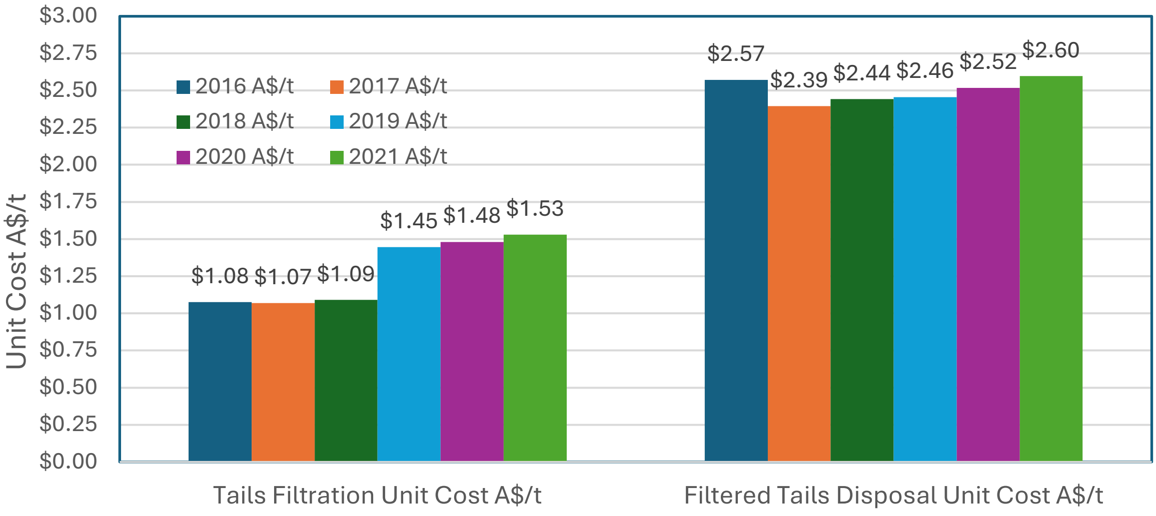


Figure 23 Operation cost for filtration and filtered tailings disposal

9 Summary and conclusion

The limited understanding of FTSF has created intensive debate on its feasibility and cost effectiveness as an alternative to conventional wet tailings. The paper has presented practical insights and experience from currently the largest tailings filtration and dry stacking operation. Some key learnings are summarised below:

- The critical success factors for filtered tailings storage option rest with the design of the dewatering equipment to suit the tailings characteristics such as gradation, particle density, mineralogy etc. to achieve design moisture content, maximum availability, and design throughput.
- The filtered tailings moisture that meets the geotechnical requirements of the tailings in the storage facility is the primary driver for setting performance criteria for filter design and therefore requires collaboration between process design, dewatering, material handling and geotechnical design team.
- Due to the maintenance-intensive nature and numerous factors affecting filtration efficiency and filter availability, filter sizes and numbers should include adequate levels of redundancy. Critical parameters such as filter cycle time must be set to optimise target throughput and filtered tailings moisture content. Performance of filter cloth is critical for filtration efficiency and filter availability.
- Filtered tailings material handling, disposal method and equipment should be carefully selected and designed for the throughput, site conditions, life of mine etc. For low throughput operations less than 15,000 t/day, trucking appears economical if terrain/topography does not impose constraints on truck movement. For large throughput operations, mechanical conveying and stacking become more cost-effective, efficient, and provide operational control of the large volumes of tailings.
- The material handling and disposal system adopted should consider tailings variability, production rates, stacking issues and other operational factors that create the need for emergency handling.
- Engineering design of the FTSF should evaluate the tailings saturated and unsaturated properties over a wide range of moisture contents anticipated from the filtration process to predict potential issues and in-situ performance of the tailings under service conditions over its lifecycle.
- FTSF is operationally intensive and requires good maintenance and asset management planning. Tailings moisture monitoring, equipment inspections, and a preventative maintenance program that ensures system reliability and high availability should be established and implemented.

- Field observations indicate that, in dry climatic conditions or low rainfall areas, tailings filtered and stored in a partially saturated or unsaturated state tend to maintain this state over time, with low risk of water table developing. In such conditions the in-situ tailings achieve hydraulic and shear strength characteristics that mitigate failure risks normally associated with conventional wet tailings. Tailings filtered to and deposited at high moisture contents tend to maintain saturated state over time and should be controlled to the minimum during operation.
- Although higher than conventional wet tailings, operating costs are still reasonable when lifecycle costs and risks are considered.

In conclusion, filtered tailings and dry stacking are feasible in terms of engineering performance and scale of operation. Advancements in design of filtration, material handling, and disposal equipment have made this option feasible for high throughput operations with reduced risks. Careful design considerations of tailings material characteristics, moisture content control and operating discipline are critical success factors for FTSF operation. In low rainfall areas or where conventional tailings failure risks are high, dry stacking should be explored as an alternative.

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