

Filter-Pressed Dry Stacking: Design Considerations Based on Practical Experience

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ABSTRACT: Filter pressing is a viable and proven tailings management alternative. Building on the experience at successful dry-stack operations, operating at production rates of up to 30,000 tonnes per day, filter-pressed dry-stacking can be (and is being) considered as an economically feasible tailings management alternative for even higher production rates. The paper presents a discussion of design basis and operational approaches based on the author's direct experience on operational projects in a variety of climatic conditions as well as ongoing feasibility studies for much higher throughputs currently planned. The paper considers limitations of currently available filtering technologies (in particular filterability of various types and grinds of tailings streams and target and achievable moisture contents of the resulting filter cake) as well as geotechnical and geomechanical properties of the filtered tailings relative to design, operations and overall performance of the dry-stack. The paper further describes mechanical conveying equipment and placement (or stacking plan) strategies including considerations with respect to lift thickness, rate of rise and pore pressure generation considerations. The paper highlights the author's experience with successful dry-stacking strategies and addresses some common misconceptions and constraints with respect to geotechnical and hydraulic performance of dry stack tailings, based on actual lab and field data presented. While not necessarily "dry" filter-pressed tailings may be conveyed or transported by trucks and are amenable to stacking and compaction (for structural zones) or placement via conveyor to angle of repose (for non-structural zones) in various stacking approaches. The advantages with respect to water consumption, reduced and/or flexible stack footprints and geometries, seepage control requirements, closure/reclamation costs and public perception of risk can result in dry-stacking being selected as an economically beneficial alternative, particularly if life of mine risks and costs are appropriately considered. As with any conventional tailings management approach, careful and diligent planning, engineering and operational controls, QA/QC; instrumentation and monitoring, is required to manage risks and uncertainties.

1 INTRODUCTION

Filter-pressed dry-stacking (or filtered tailings) has been proven as tailings management alternative for currently operational facilities at production rates of 2,500 to up to 30,000 tpd. A sample of currently operating dry-stack tailings facilities are identified, by daily tonnage, in Figure 1. There are many studies and proposed projects considering significantly higher production rates in the order of 100,000 tpd.

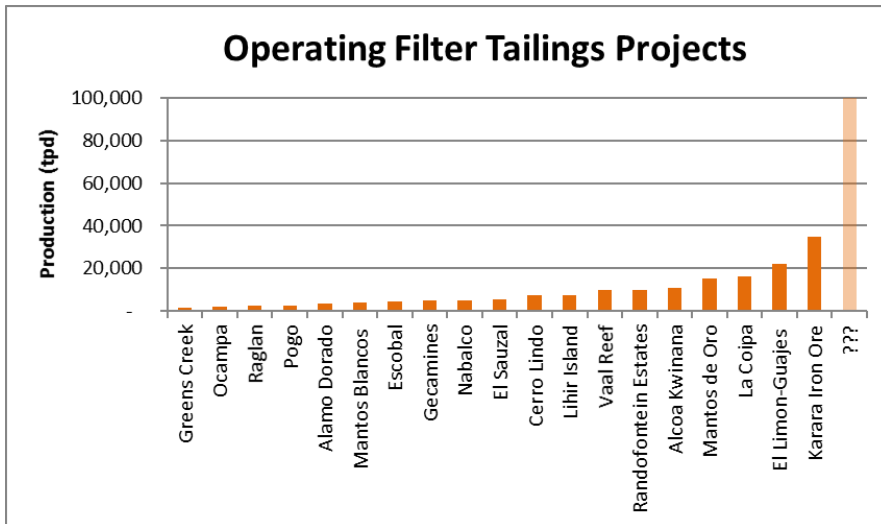


Figure 1. Operating Filter Tailings Project (dry stacks)

However, there remains significant industry uncertainty related to achieving economically viable filtration and stacking at high throughputs (on the order of 50,000 to 100,000 tpd, or more). Concerns related to filtration efficiency (and cost), efficient material handling and placement at high throughputs, operational controls and high operating costs to achieve physical stability are among the challenges to be addressed. The physical stability of 100 to 200 m high planned stacks—a consequence of the planned production volumes on the order of 50,000 to 100,000 tpd or more—warrants careful consideration with respect to design basis assumptions and achievable strength and density of stacked materials, affecting overall performance. Capital (CAPEX) costs for a high production rate dry-stacking operation may be of the same order of magnitude as conventional approaches, but managing operating (OPEX) costs and ultimately closing the gap on cost differential between dry-stacking and conventional slurry and alternative (paste, thickened and cyclone) tailings management alternatives is highly dependent on selected stacking approaches and strategies for managing these identified risks and uncertainties. Haul distance, placement strategy and compactive effort in structural zones, as well as re-handling of off-spec materials can significantly increase the unit cost of a dry stack facility in comparison with a more conventional impoundment. To reduce the risks and uncertainties associated with potentially high OPEX costs requires close interface between owners, designers, operators and equipment vendors in planning and execution stages. Tight constraints and maintaining cost-effective operational controls (including QA/QC, instrumentation and monitoring) for high production rates are also a challenge, but no more than for conventional facilities of similar heights and volumes.

2 FILTRATION

2.1 Filterability

Plate and frame filter-press may be increasing in size (from 2x2 and 2.5x2.5 m to 4x4 and 5x5 m plates), but the fundamental underlying technology has not advanced significantly in the last 20 years. Current advancements in the actual filtration technology seem to be primarily focused on reducing OPEX costs (e.g., more durable filter cloths and process efficiencies with respect to cycle time, air blow, wash cycles, etc.). Nevertheless, almost all tailings are filterable. The question remains at what efficiency (cost) to achieve the desired target moisture contents and whether stacking strategies can overcome the inevitable gap between desired (target) and actually achievable filter cake moisture content. It has been the authors' experience that only some unique residues (e.g., from rare earth metal mines, containing significant amounts of gypsum and other process chemicals) result in material that is truly not filterable. Some typical gradation curves for

a range of dry-stack projects (in which the authors have been involved) are plotted in Figure 2. The percent fines (silt-sized fraction passing the #200 sieve) and clay-sized fraction (< 2 microns) affect the efficiency of the filtration process and the required filter pressures and cycle times, and the resulting consistently achievable filter cake moisture contents, but all have been filterable. The potential for true clay mineralogy as opposed to rock flour with clay sized fraction is important to distinguish when considering filter-pressing efficiency. Significant challenges including clogging of filters can occur, if the clay-sized fraction is truly a clay mineralogy and present in a significant portion of the tailings.

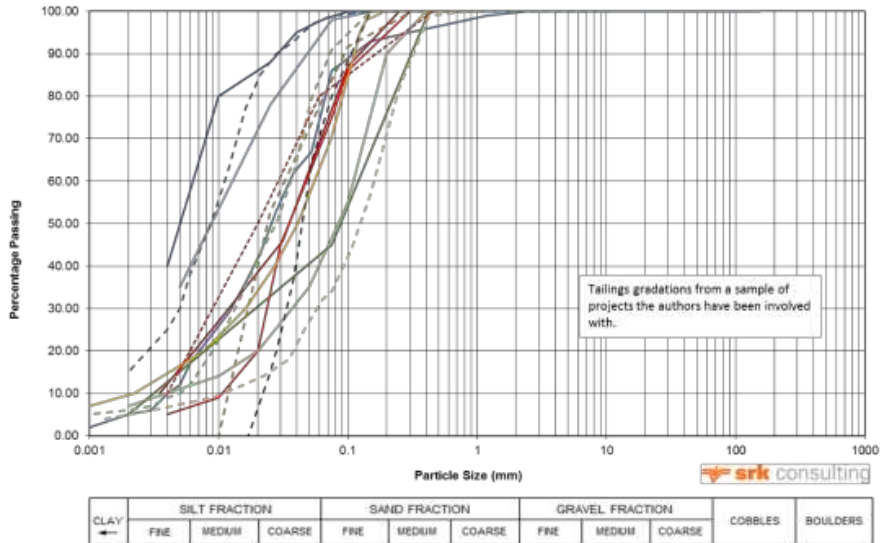


Figure 2. Typical gradation curves, filtered tailings

The tailings engineer has no control over the desired grind for recovery (or gradation of the tailings) or the production processes that may result in tailings stream with significantly different gradations. Nor do engineers and operators have significant control over the variability of the ore which may be the controlling factor in achieving consistently economical filter-pressing. Often, clay mineralogy zones are generally short-lived in terms of life of mine and if this variability is anticipated and accounted for, placement strategies to manage high moisture content (less efficiently filter-pressed) filter cake over relatively short durations can help manage this risk.

Consideration of the potential for variability in the tailings gradation and or percent solids by weight feed to the filter presses are key factors to be considered. Tailings variation has always been present in mining operations but filtration and dry stacking is more sensitive to these variations than conventional storage methods. Often the filter pressing operations can handle short-lived variability in clay content, as long as it's not also compounded by a significant and potentially longer duration variability in the solids feed due to rheological constraints at the thickeners. Engineers and designers should not focus solely on a single or average particle size distribution from a limited pre-production metallurgical or pilot testing tailings sample for planning and design. The range of particle size distributions in Figure 2 could just as easily be considered a range in variability of ore and grind over a number of years (life-of-mine) and this should be kept in mind when considering the potential variability during operations. Often the designer is provided with limited and potentially unrepresentative samples of tailings in the early stages of a project, and it is therefore important that consideration be given to the mine plan and ore body geological information in considering the likelihood for variation in ore properties.

With respect sensitivity to grind variability and/or the variation in particle size distribution from various process streams —where a process stream may result in a much finer gradation and/or represent a greater risk of low efficiency overall than other streams—there is a benefit to filtering the challenging waste streams separately and accepting a lower efficiency of pressure filtration for this single stream, only. Combining the filter cake after the fact, rather than the combined waste streams before filtering, may be more cost effective. Lower efficiency (higher moisture content) streams can be managed by placing in the off-spec (or non-structural zones) of the dry stack. Separate filtering and handling of potentially acid generating tailings streams may also prove to be more effective. These streams may similarly be filtered separately and co-disposed or encapsulated within designated zones of the dry-stack.

2.2 Achievable vs. Target Moisture Contents

When discussing filterability, it is a common misconception that the tailings material can and must be filtered to a specific target moisture content (often cited as 15% in technical literature and by vendors). Three key points are made: 1) an average target moisture content of 15% is just that, a target, and the consistently achievable moisture content is often significantly higher; 2) the volumetric moisture content is several percent higher than the geotechnical (or gravimetric) moisture content; and 3) the “target” moisture content from the filter press (whether defined as volumetric or gravimetric) should be in line with the required facility design criteria, stacking plan and performance and can therefore vary significantly between various facility zones (structural and non-structural) and facilities, depending on location, climate, stack geometry and other factors. For example, the Alcoa Operations in Kwinana, Western Australia, operate a filtered tailings facility with a target moisture content of 30%. This was determined to be the acceptable filter cake moisture content, based on deposition strategy and the arid environment. The Karara operation in Western Australia (see Figure 3) considers the more typical average target moisture content of 15% and average achievable of 18% acceptable, again based on environment, deposition strategy and stack geometry. The Escobal Mine operation in Guatemala has a similar target moisture content of 15% and average achieved moisture content of 18%, however based on high seismic risk and stack geometries an additional target moisture content on the order of 12-13% has been specified as part of stringent compaction requirements in structural zones.

Commonly, projects are specifying (or promising) a target filter-cake moisture at the limit of the filter performance (including at the limit of the thickener’s ability to deliver feed at the required solids ratio). This has caused numerous examples where the operating performance does not consistently meet the target. The authors’ have consistently seen results similar to those presented from the Karara project in Figure 3, with respect to achieved versus target moisture contents. Essentially, irrespective of site, ore body type, or filter press manufacturer, a 15% moisture content remains a typical target, while tracking of day-in and day-out moisture contents of filter cakes demonstrate that achievable moisture contents are often in the range of 17 to 18% when things are running smoothly and can be up to 20 to 23% when off-spec.

The authors suspect this difference in target versus achieved moisture content, irrespective of ore body type, has to do with a variety of limiting factors in combination with specifying the target moisture at the limit of the filter performance: (a) tailings gradation and mineralogy variation; (b) limitations on thickening and rheology controlling the solids content feed to the filter presses; (c) limitations of efficient and cost-effective cycle times with higher fines/lower permeability tailings, and (d) degradation of filter cloths resulting in varied performance for the same tailings material.

Notably, this is also evident in the long term and not just during commissioning. As can be seen in Figure 3 the scatter of the moisture content results reduces with time but the overall trends remain.

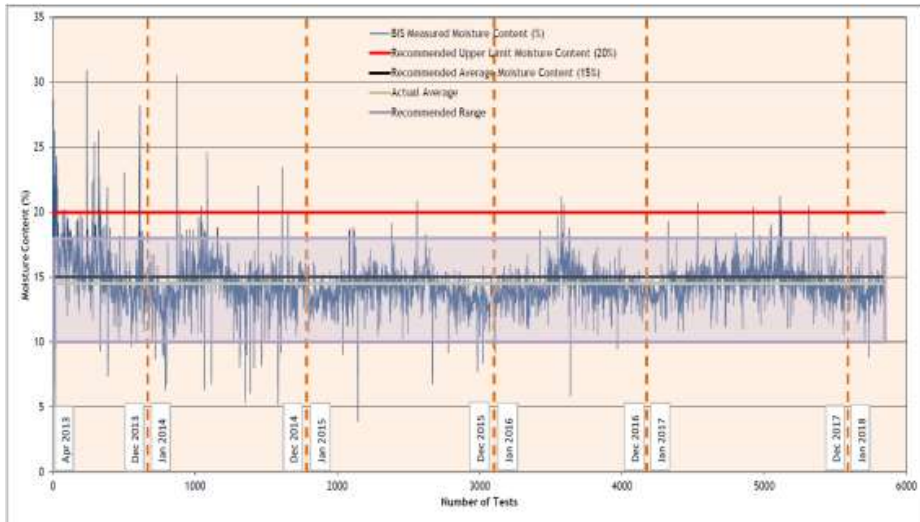


Figure 3. Anticipated target vs. actual range of achievable moisture contents (image source: Nelson Amoah, published materials, April 2018)

Coarser tailings overall will be more efficiently filter pressed and will usually be able to produce filter cakes at moisture contents at or near optimum for compaction, but in general in the range of anticipated grinds achievable moisture contents, at current state of the technology, are generally higher (and often significantly higher) than the optimum required of structural zones. See Figure 4 for definition of structural zones after Lupo, 2010.

As illustrated by Figure 3, “targets” may be cited or promised, but achievable filter cake moisture contents and the variability of the process are not generally within the tailings engineer’s control. The tailings engineer can, however, specify acceptable moisture contents for different areas of the dry stack, depending on stacking strategies. For example, external structural zones may have more stringent criteria than non-structural zones, for which reduced constraints may be allowed. The author’s approach more typically specify target moisture contents at the operating deck, considering conveyance and stacking approaches for achieving specific performance objectives for the overall geotechnical and physical stability of the landform, considering both static and potential seismic loading conditions, drainage, rate of rise, consolidation, and overall stack height and geometries.

2.3 Off-spec tailings

During operations the requirement for off-spec tailings storage is reduced (but not eliminated) after start-up as the processing systems are optimized and stabilized and effective stacking approaches are refined. If the filter plant is set up with multiple presses and redundancies or spares, the likelihood that all the presses going down together are low, and the need for a separate conventional impoundment for off-spec materials (un-filtered tailings) is generally not a requirement during operations, but may be during commissioning. During commissioning, the dewatering systems can commonly underperform. This can be exacerbated with operational efforts often concentrated on the ore processing and mineral recovery systems during this period.

As noted, off-spec materials are commonly defined as materials having moisture contents above 18 percent (or on the order of 20-22 percent), depending on the target moisture content for the facility. What is typically required for managing these materials is an emergency radial stacker and sufficient stacker pad area to provide for temporary storage piles of filter cake. Providing for both a large stacker pad and large operational deck is also of great value to maintain operational flexibility. A temporary storage area(s) of filter cake material placed for 8 to 10 days (at least) via an emergency radial stacker near to the filter building area is recommended for operations, with larger potentially required at commissioning. Operational flexibility on-deck should also be

provided with back-up plans for truck transport and dozer pushes if mobile stacker and conveyor systems do not have sufficient redundancy. For conveyor transport systems, it is more likely that the conveyor system and mobile stackers would need a back-up plan.

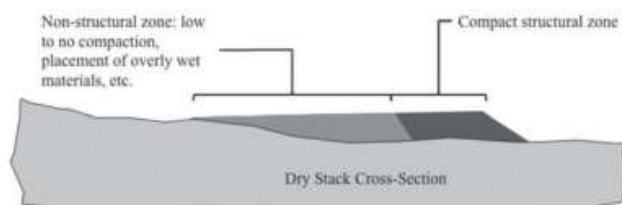


Figure 4 Consideration of a Structural (Compacted) Stability Zone (Davies, Lupo et al 2010)

3 STACK / LANDFORM PLANNING, DESIGN AND CONSTRUCTION

3.1 Climate

Achieving a physically stable landform in wet and cold environments will not be accomplished in the same way (i.e. with the same disposal strategy and operational requirements) as in an arid locale. Moreover, scalability of solutions may become highly non-economical if the approach for achieving a physically stable landform becomes operationally demanding. Therefore, as any other type of tailings facility design, climatic conditions and production scale will have a great impact on the design and operational approaches to dry-stacking.

Arid climates have been the first to embrace higher production rate dry stacking projects, typically driven by the economics and scarcity of water for processing, but also due to permitting and land acquisition constraints. Dry stacks in these climates can utilize the high evaporation potential to further enhance the dewatering process and ensure the stack will remain unsaturated. Deposition in thin lifts/faces over large areas can result in significant additional drying of the tailings. However, it should be noted that transport and deposition by trucking and compaction will limit impact and effectiveness of evaporative drying. Facilities with conveyor stacking arrangements placing loose material in thin faces will achieve higher evaporative drying, but this may still be limited to the outer few centimeters depending on stacking cycle time.

Wet climates face additional challenges with surface water management and typically must employ active management of the operating deck to facilitate high run-off. Radial stackers, stacking filtered materials in relatively steep piles that readily shed water during intense storms is also one operational approach that has been implemented.

Cold climates—defined here as climates where freeze back of tailings can be expected in the short or long term—can and do successfully employ dry stacking technology. The Raglan Project (Quebec, Canada) and Pogo Project (Alaska, USA) are two examples of operational facilities in cold climates. In addition, the Hope Bay Project (Nunavut, Canada) has a designed dry-stack facility undergoing final permitting and expected to be developed in the next few years. Freeze back of the tailings can be advantageously used in these environments to improve stability and minimize seepage potential. A common industry concern is the freezing of tailings prior to placement causing issues with equipment and post placement density. This is a balance of transport method and time with climatic conditions. The authors have found that this is typically not an issue even in the high arctic when transporting with trucks. Thermal modelling for conveyor transport can be undertaken to determine the maximum exposure period for the tailings at a given climatic conditions. It is also noted that freezing of the tailings, post placement and compaction, will result in a reduction in dry density of the placed tailings and an active layer will develop in the stacked landform. The freeze-thaw impacts and associated density reduction should be considered in stability analyses of the stacked landform.

3.2 Conveyance and Transport and Deposition

Either trucking or conveying can be used effectively for filtered tailings. The decision is typically driven by the economics of the project. Typically, the authors have found that trucking as the primary transport methodology is only cost effective for production rates below 10,000 tpd. For higher production rate operations, conveyance, including mobile stackers and innovative stacking approaches utilizing long-reach radial stackers, is typically required to minimize placement and handling (including re-handling) costs.

The filter cake is generally amenable to conveyance and transport at higher moisture contents than are acceptable for stability zones. As such, alternative methods of materials drying and handling (including solar and wind evaporation) of thin lifts may be required to achieve desired moisture contents and densities for the overall physical stability of the stack. Target density can be achieved by compaction of structural zones, but several approaches have been used for reduction of moisture content post filtering including thin lift deposition when advance stacking (such as at Karara, as illustrated in Figure 5). Similarly long-reach, retreating mobile radial stackers are being considered for several planned large tonnage facilities.

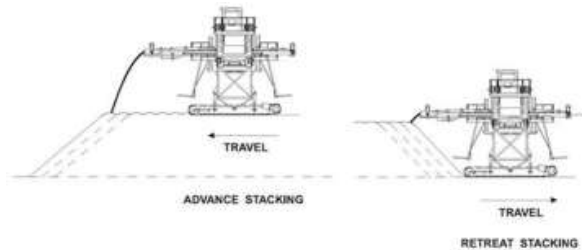


Figure 5 Alternative Stacking Approaches (Luppnow and Hore, 2014)

3.3 Rate of Rise and Pore Pressure Generation

Depending on efficiency of the filters, the variability of the ore, other operational constraints, and poor operational control there is a very reasonable risk that low-density, high-moisture content filtered tailings will be placed within the dry stack. Figure 6, illustrates that at the range of typical target and achievable moisture contents, it is more likely than not that the tailings will behave as a saturated material unless arid conditions prevail and/or other moisture conditioning measures are not taken during placement.

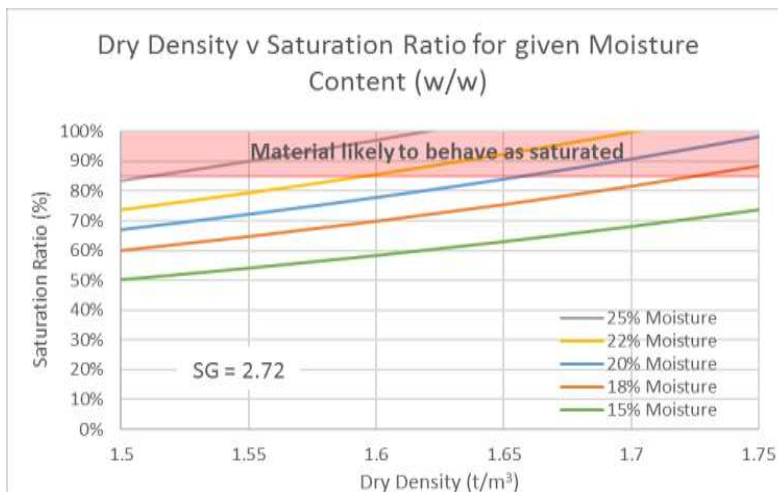


Figure 6 Dry Density vs. Saturation Ratio for given Moisture Contents

As with conventional tailings facilities, managing the rate of rise over critical areas is also particularly important to allow time for consolidation and drainage to occur and for any developed excess pore pressures to dissipate, particularly if the filter cake is placed significantly wet of optimum.

Pore pressures may increase in localized zones, but if the rate of rise is adequately managed to ensure that mobilized stresses are less than the in-situ and/or residual strength of the materials, it is the author's experience that localized excess pore pressures within the stack generally dissipate within a few weeks or months of initial placement of a given lift. Balancing the rate of rise with rigorous instrumentation and monitoring to verify the actual dissipation of pressures once stacked can be a key part of the overall engineering and operational control of the dry stack to minimize and/or mitigate risk, particularly at high placement/production rates. If the tailings become and/or remain saturated, they can be susceptible to pore pressure increases and associated strength reductions as well as static and seismic liquefaction.

Special attention will need to be paid to the drainage conditions base of the stack, as dry stacks are not "dry" and lower layers may become saturated during stacking of subsequent lifts. The basal layer can often be the layer with the most off-spec, high moisture content material as it is placed during commissioning when the operation of the filters are being optimized. This reinforces the need to have adequate off-spec and QA/QC during operations over the entire life of mine to create and maintain a geotechnically stable landform.

3.4 Stacking Height and Overall Physical Stability Performance

Stack heights upwards of 100 m may be pushing the boundaries of the state of empirically based knowledge of the application of this technology, with respect to the stress states and strengths within the stack, particularly if compared with more conventional earthen embankment or dam heights. But this is no more or less true than the heights being pushed with more conventional facilities and cyclone sand dams. These are challenges and do represent risks and uncertainties, but these challenges are within our ability as engineers to evaluate and monitor.

Application of critical state soil mechanics can help us understand the limitations for stacking height (and the response of a given lift to subsequent lifts) with respect to the stacked tailings moisture content and density. Dense materials dilate while loose materials contract during shear to reach a common void ratio at large distortional strain (i.e. the critical void ratio). With respect to filtered tailings, individual lift thicknesses exceeding conventional earthworks compacted lift thickness (on the order 12–18 inches or 0.2 to 0.3 m) will result in stacked tailings that are contractive, regardless of climatic or other stacking conditions.

If filtered tailings are placed in excessive lifts and/or at angle of repose (i.e. not compacted to a dilatant state), they can exhibit contractive behavior under future loading (whether static loading under subsequent lifts, or seismic loading due to earthquake events). Even if dry (unsaturated), low-density lifts on the order of 20 to 30 meters placed with advancing or retreating mobile stackers are still at risk of being contractive in response to subsequent loading (including by the next 30 meter lift). Under shear, contractive tailings could lead to very low static undrained shear strengths, even under static conditions, within the dry stack. Liquefaction of stack can be avoided if the stack (including basal zones) are placed and remain unsaturated and/or the structural zones are placed (and compacted) to an adequately dense (dilative) state. To preclude this, and associated strength loss and excessive deformation of the stack whether static or seismic, key structural stability zones must be compacted to a dilative state, typically requiring mechanical compaction at moisture contents at or slightly dry of optimum.

3.4.1 Co-mingling/Co-disposal

There always remains the alternatives of co-mingling (mixing filtered materials with dryer coarser materials) or buttressing (with amended tailings zones or borrow or waste rock co-disposal) which can significantly reduce the filtering constraints on all or a large portion of the tailings across the life of mine.

These co-mingling/co-disposal and buttressing approaches have their own challenges, risks, and associated operational cost considerations. However, they may offer needed operational flexibility and present a toolbox of approaches when handling increased production, increased

heights, potential for changing conditions and challenging climates (as already demonstrated at several operating stacks), and a number of bench and field-scale pilot studies.

4 SOME ADDITIONAL RISK CONSIDERATIONS

4.1 Infiltration and Seepage

Limiting the potential for excess pore pressures development may also be managed by limiting infiltration or subsequent rewetting of any given lift once placed. In general, if the permeability of the placed filtered tailings is low (on the order of 10^{-6} cm/s or less) the tailings mass can be highly resistant to infiltration and saturation and, in general, seepage within the stack is governed by unsaturated hydraulic conductivities (AMEC 2008).

Operational controls on the upper surface can also manage infiltration and surface water run-on, run-off and ponding to also minimize infiltration to the overall stack. Safety berms around the edges of dry stack need to be carefully placed with adequate outflow points along with grading of the upper surface to ensure ponding and infiltration does not occur at the outer edges. This can be an issue even in arid climates as has been seen at Karara.

Moisture retention and unsaturated hydraulic conductivity characteristics of the filtered and stacked tailings can be established relative to seepage potential. However, in general, there is a finite and limited (transient) volume of entrained water remaining in the filter tailings available to seep (as illustrated in Figure 7) governed by unsaturated flow as compared to significantly higher volumes governed by saturated flow of more conventional facilities.

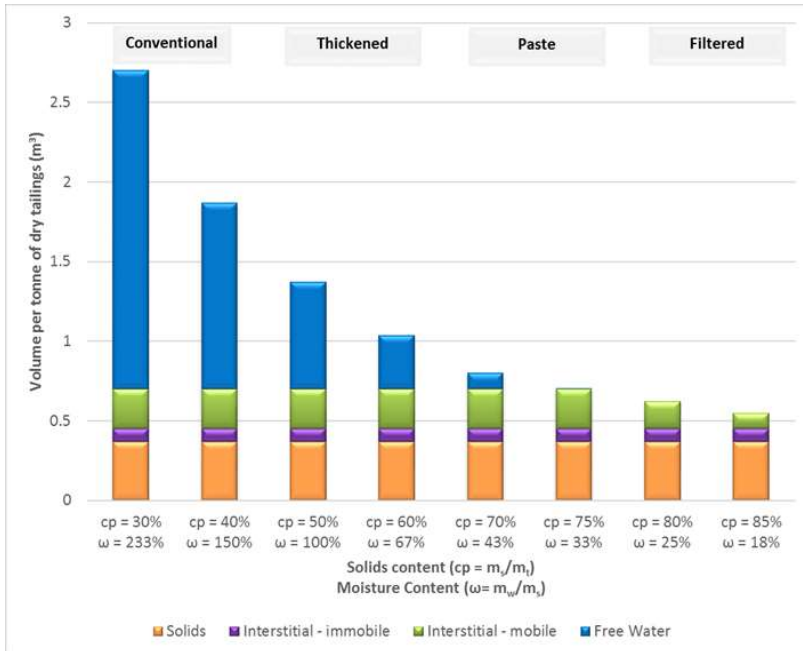


Figure 7 Free vs. Interstitial (mobile and immobile) Water Comparison – Alternative Tailings Technologies

For generally fine grained tailings of relatively low permeability, it has been the author’s experience as previously concluded by Davies and Rice (2001) that with respect to infiltration and seepage:

“If there is proper compaction and maintenance of target moisture contents, seepage is negligible, and instead of creating a complex system to capture seepage that will likely never appear, spend those resources more appropriately on surface water management measures

that include a collection pond downgradient of the dry stack. Resaturation of properly placed and compacted filtered tailings is extremely difficult and not the concern many presume.”

Instrumentation and monitoring for both infiltration and seepage will serve to help manage and mitigate risks and uncertainties.

5 COST AND COST RISK CONSIDERATIONS

Haul distance, placement strategy, and compaction effort in structural zones, as well as re-handling of off-spec materials, can significantly increase the unit cost of a dry stack facility in comparison with conventional storage facilities. To reduce the risks and uncertainties associated with potentially high OPEX costs, a risk management plan including close and ongoing interface between owners, designers, operators, and equipment vendors in planning, design and execution stages is required. Not unlike conventional facilities.

Based on the authors experience on operating dry stacks and engineering estimates performed for current prefeasibility and feasibility dry-stack projects of various production scales, it is our finding that CAPEX costs for dry-stacking do not generally represent a significant increase over conventional tailings CAPEX—at least they are not the determining factor. OPEX, however, for dry stacking approaches can represent a significant differential that may or may not be offset if project wide and life-of-mine costs are appropriately considered. The OPEX for conventional facilities is on the order of \$1.00 tonne. By comparison the OPEX for dry stacking can in the order of \$2.00 to \$3.50 per tonne of dry tailings in the authors’ experience. This range of OPEX dry-stacking is lower than previously published guidance based on older databases and which presumably reflects technologies, operational constraints and potential re-handling considerations of early projects. On the basis of the experience of the operating facilities, constraints are continually being evaluated and optimized as the industry works hard to plan and demonstrate the economic viability of higher production rate dry-stack facilities. More recent preliminary economic assessments have reported lower projected OPEX costs per tonne for planned high tonnage dry-stack projects as reflected above. Further development of the method has and will likely continue to narrow the differential in the range of OPEX costs between conventional and dry-stacking, but the differential is likely to remain at least \$1.00 to \$1.50 per tonne higher than the currently estimated cost of slurry disposal, for the time being.

Offsetting this OPEX differential requires careful, project-specific consideration of all costs and risks, particularly those key cost differentiators that have a very real potential to make up cost differentials over the life-of-mine. These may include land acquisition, water makeup, borrow, liner, reclamation costs, and costs of delays to the project based on permitting and stakeholder perceptions of risk. The risk costs associated with conventional facilities with significantly higher consequences of failure relative to dry stack facilities should be incorporated into the economic assessments.

6 CONCLUSIONS

Filter press tailings facilities have been in successful operation for over 30 years. More and more mines are using or considering the approach. There are limitations and challenges. However, the filter press manufacturers, the design engineers, and the mine operators are rising to the challenges and we can expect more advancements to come. The argument of scale alone should not be used to eliminate dry-stacking as a tailings management alternative.

With the appropriate management of costs and risks, dry stacking is an appropriate technology for tailings management. With a shifting industry, public and regulatory level of risk tolerance, dry stacking will likely continue to become more favorable.

With respect to operational cost differentials (as compared to conventional slurry or cyclone sand dam facilities), it is the authors’ experience that appropriate and holistic consideration of the true life-of-mine costs and risks, as well as appropriate planning and execution of engineering and administrative controls has the potential to further reduce the current differential in OPEX as compared to conventional facilities. The result is the filter-pressed dry stack will more and more be considered an economically viable—and even preferred—option when considering higher tonnage projects.

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