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How to compact filtered tailings

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Abstract

To control the risk of static or dynamic liquefaction, filtered tailings stacks are typically designed to be compacted and to remain unsaturated. In theory, compacting filtered tailings should be easy, since mines tend to produce a consistent, well-graded sandy silt or silty sand tailings. The filter presses are designed to produce tailings with a geotechnical moisture content within a narrow range; modest-sized equipment can compact the tailings in thin lifts; and traditional earthworks quality control methods are common and readily available.

In practice, however, filtered tailings and mine owners often discover that the learning curve associated with compacting filtered tailings can be steeper than expected.

The filter plant will typically produce tailings that are somewhat wet of the standard Proctor optimum moisture content, making compaction difficult. If not protected, tailings at the loadout can absorb water or freeze. The tailings stack must be kept graded to promote runoff. In some climates, evaporation may be insufficient for drying; in others, snow, ice, and freezing conditions present a challenge. At some mines, the tailings liquefy under cyclic loading by dozers, trucks, or compactors as they are being placed.

Choosing a tailings field-density specification is not straightforward, especially where high stresses at the base of the stack can increase the risk of static or dynamic liquefaction. Method specs for compaction may be employed, but can be unreliable under certain conditions. A nuclear densometer often does not provide accurate readings of the density of some tailings, particularly those with elevated levels of metals.

This paper presents practical, hard-won lessons and solutions from the field to aid in the design, operation, and closure of filtered tailings facilities based on firsthand experience in Canada and interviews with operators around the world, lessons that can help shorten the learning curve for new and existing filter stack operations.

Keywords: *compaction, filtered tailings, earthworks, geotechnical, landform design, density, liquefaction, moisture, tailings stack, quality assurance, quality control.*

1 Introduction

Many mines are already using filtered tailings technology for a variety of reasons, including rapid recovery of process water and reduced risks related to managing slurry tailings dams. Others are considering such approaches. A filter plant is constructed to desaturate the tailings, and the tailings are conveyed or trucked to a tailings storage facility (TSF), often referred to as a filtered tailings stack (the term ‘dry stack’ has fallen out of favour at many operations (Ulrich & Coffin 2013) given the large quantities of process water still present in tailings pore spaces and the potential for resaturation). Filtered tailings are typically a sandy silt, but recent advances in filtration also allow for the economical treatment of some high-fines tailings (Lupo & Hall 2010). These facilities are usually regulated as tailings facilities yet are designed to have more in common with mine rock stockpiles in that they contain no free and/or ponded water, and most are designed to avoid containing potentially contractive/mobile tailings.

Filtered tailings are used in many climatic settings, from arid desert to coastal temperate rainforests, continental, and sub-arctic. Each setting presents its own challenge, particularly sites with high rainfall or freezing temperatures.

Static and dynamic liquefaction are two common potential failure modes for external tailings facilities. A filtered tailings stack is designed for geotechnical stability, typically using two concurrent methods – the facility is underdrained to limit saturation of the tailings, and the tailings are spread in thin lifts and compacted to a dense (dilative) state. If there is concern that either of these conditions may not be achieved or maintained, a lower-angle slope or a toe berm may be required to manage stability.

While compacting filtered tailings is straightforward in theory (and usually much simpler than managing dykes and slurry tailings), many mines struggle in practice with the compaction of filtered tailings, especially during start-up and the first few years of production. MEND (2017) highlights one of the main risks for filtered tailings stack operators: ‘not being able to meet material specifications consistently during construction, which increases the likelihood of slope failures.’ This paper explores the difficulties many operators encounter and the associated solutions that have been tested in the field.

None of the geotechnical lessons described below are new. Lessons are most often learned when planners, designers, or operators are overly optimistic (Burnett & McKenna 2022). Addressing these fundamental issues in design and early construction will help operators design effective filtered tailings facilities, construct them to that design, and achieve the required performance in operations and closure. Successful implementation of any new tailings technology or extension of an existing technology beyond precedent requires a sceptical attitude and a constant checking of basic geotechnical assumptions, as described further.

Key papers and resources on the design of filtered tailings stacks include those by Davies & Rice (2001), Davies (2011), UBC (2021), Ulrich & Coffin (2013) and Davies et al. (2022). Hore (2020) provides a succinct overview, while Vargas & Campomanes (2022) provide a detailed overview of filtration and stacking based on data from 28 sites worldwide. MEND (2017) provides a useful comparison of tailings technologies, including filtered tailings. Condon & Lear (2006) provide a classic summary of lessons learned from a tailings stack in a coastal rainforest. Methods for closure planning and landform design of tailings facilities are well summarised by Andrews et al. (2022).

2 Background

Tailings are the mineral residue of ore milling and are typically comprised of angular, silt-sized particles of crushed rock, but may also originate from the processing of natural mineral sands. They typically contain large volumes of water (forming a slurry) and may contain residual reagents and elevated levels of metals, salts, and other constituents of concern.

2.1 Filtering and filter plants

Mine tailings have traditionally been slurried to an external containment structure or deposited back in-pit. Filtering is becoming more common among the dozens of available tailings treatment methods (CTMC 2012; Davies et al. 2022). Tailings are subject to vacuum filtration or passed through belt presses, filter presses, or, in some cases, centrifuges. Typically, the excess water (filtrate) is recycled back to the plant, and the filtered product (cake) is transported by conveyor. Some initial dewatering before filtration (often using thickeners or cyclones) is often employed. Tailings may be directly conveyed or hauled to their ultimate disposal site (the stack) or stockpiled for hours or days adjacent to the filter plant before permanent placement. Figure 1 provides an overview of a typical layout.

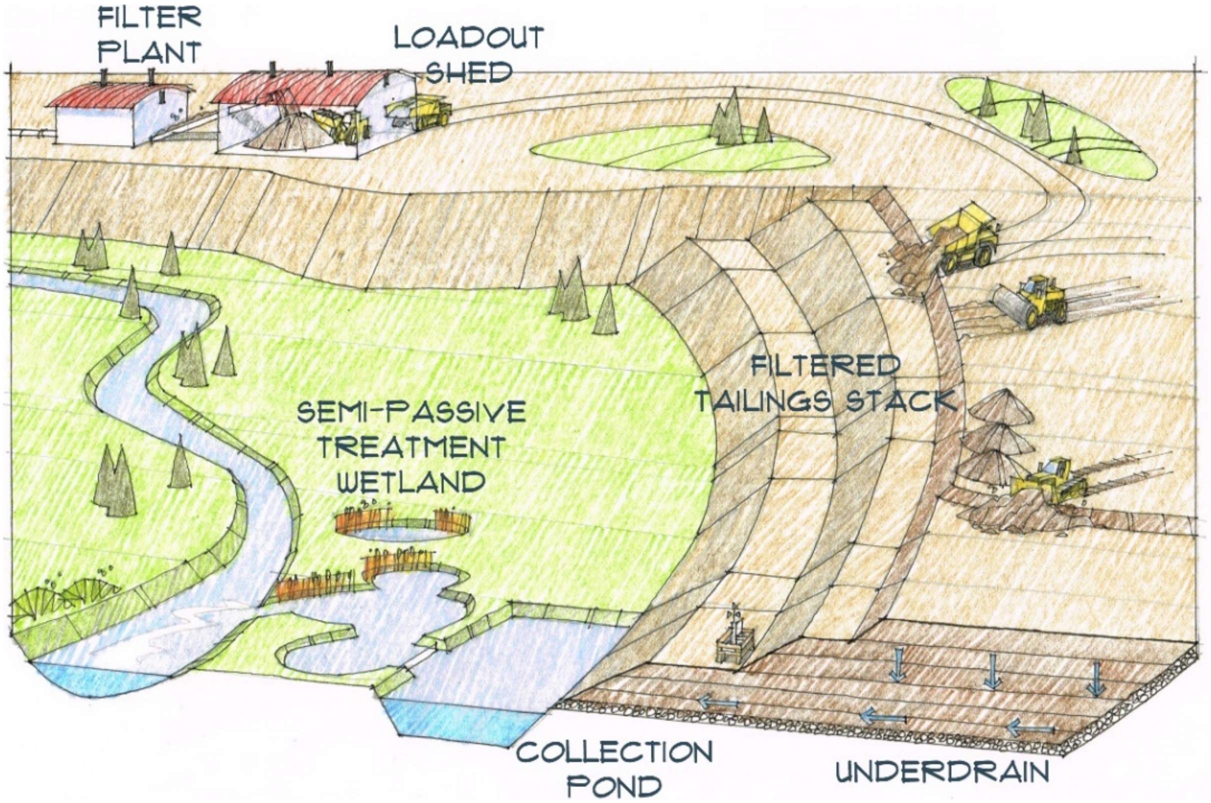

Figure 1 Common components of a filtered tailings production/stacking operation

2.2 Facility underdrain

The filtered tailings stack has a prepared base that may include a liner and a sand or gravel underdrain, supplemented at some locations by slotted drainage pipes. The intent is to minimise the saturation of the tailings by groundwater ingress, or by net percolation during operations and post-reclamation periods. The drain may also collect any contaminated seepage from the stack.

2.3 Compaction

The compaction of earthworks is a mature technology that is well understood by geotechnical personnel. Mobile mining equipment is used to spread the tailings in thin lifts, often 0.15 to 1.0 m thick (see Fell et al. 2014 [Table 14.2]), after which the tailings are compacted by haul truck traffic, dozer track-packing, or heavy compactors (often a vibratory smooth drum roller for silty or sandy tailings). For low-volume sites, the haul truck driver may also be the dozer operator and/or compactor operator. A test fill is typically used to select the lift thickness – various lift thicknesses are trialled under controlled circumstances, and the density at various depths is measured to ensure that the compaction is effective to the base of the lift. As a rule of thumb, the effective depth of compaction is often close to the bearing width of the dozer or haul truck tire). While thicker lifts are feasible with larger mining equipment, keeping lifts to a thickness of no more than 0.3 m makes measurement of the compacted density simpler. As described below, a compaction method specification may be developed during this test fill.

Using the standard Proctor density (Proctor 1933; ASTM D698–12(2021)) as an earthworks specification is routine for the compaction of filtered tailings. This laboratory test mimics the performance of field compaction using common compaction equipment. The test measures the density of a small volume of tailings placed in layers in a mould and compacted with a known effort. Various moisture contents are trialled, the resulting density is plotted against the moisture content, and the maximum density and optimum water content are determined (Figure 2). The designer chooses a target minimum dry density, typically some percentage of the standard Proctor dry density. This moisture content is typically between 60% and 80%

saturation (Davies et al. 2022). As the density increases, the tailings become stronger, stiffer, less compressible, and less permeable. If the tailings are loose and saturated, they may liquefy under equipment, static, or earthquake (dynamic) loading.

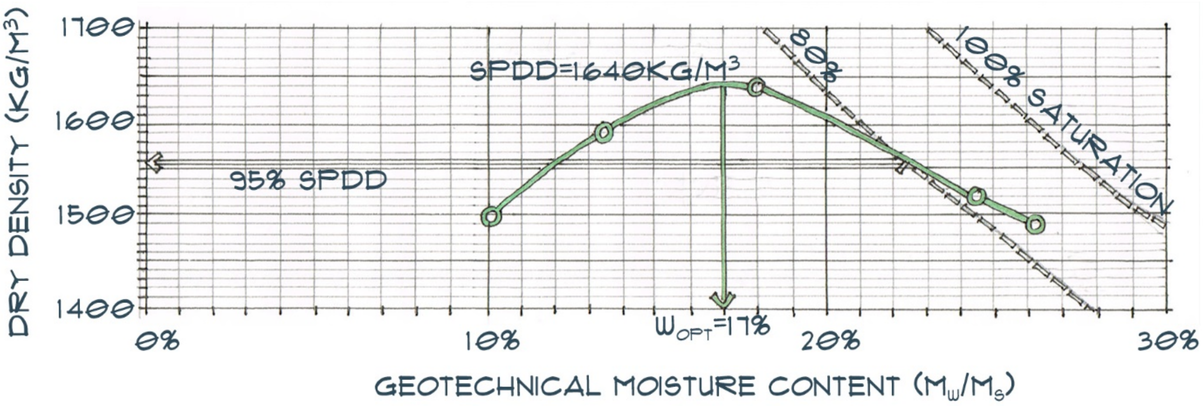

Figure 2 A typical standard Proctor dry density curve and the corresponding optimum geotechnical moisture content

If the tailings are placed dry of the Proctor optimum value, they will require additional effort (a larger number of passes or heavier equipment) to compact. On the other hand, as is often the case (e.g. Crystal et al. 2018), if the tailings are wet of optimum, they can be difficult to compact, and the compactive effort may lead to rutting or rolling, and it may not be possible to achieve the target dry density without further drying the tailings. Various methods of drying a lift of tailings in the field are available, although such methods are easier to apply in dry climates than in cold or wet climates.

2.4 Landform design

A filter tailings stack is a mining landform (LDI 2021) designed and operated to meet closure requirements. The filtered tailings are placed such that only minimal regrading is required to fit the final form, and they are usually conducive to progressive reclamation (e.g. Moore 2015). Surface water run-on and runoff controls are designed into the facility, which is designed to either avoid or accommodate resaturation and infiltration, even over the long-term, and under a changing climate. Some filtered tailings facilities are encapsulated with mine rock (e.g. Ulrich & Coffin 2013). A cover system is typically installed to limit net percolation, control erosion, and act as a growth medium for sites that will be revegetated (see INAP 2017). The slopes are often reclaimed progressively to limit erosion. Andrews et al. (2022) and LDI (2021) provide an overview of closure planning and landform design applicable to filtered tailings. Access (2003) provides an example of revegetation technologies, focusing on boreal environments.

2.5 Selecting the minimum compaction density

Each filtered tailings and each filtered tailings facility design will have its own minimum compaction density, depending on material properties and performance requirements. The designer carefully selects the minimum allowable density based on the drained and undrained shear strengths, trafficability, stiffness/settlement, hydraulic conductivity, saturation, and air permeability. The initial tailings compacted dry density will dictate the tailings performance with respect to the critical-state line, and will also dictate whether the tailings will transition from a dilatative state to a normally consolidated (and contractive) state under loading. ICOLD (2022) provides a list of design considerations applicable to filtered tailings stacks.

The configuration of the TSF is an important consideration for managing material handling and compaction. Ideally, the tailings stack will have two zones: a shell of well-compacted high-spec filtered tailings and an inner zone that allows for the safe placement of lower-spec material (Davies et al. 2022). Sometimes an outer shell of different material is used for stability and erosion protection or as part of a mine rock disposal scheme.

For most configurations, the filtered tailings placement area will decrease with stack height – designing for enough room for operations and efficient tailings placement at all stages of construction is key, particularly for the final lifts.

As noted above, the minimum design dry density specification is chosen so that the filtered tailings will act as a dense material that is not prone to liquefaction under static or dynamic loads. As shown in Figure 3, the required density is a function of the effective stress at each point in the deposit. An outdated rule of thumb that a material needs to be denser than 90% of the standard Proctor maximum dry density is a poor design basis for three reasons. First, for high tailings facilities (where stresses near the base will be high), the required density to avoid the risk of liquefaction may be well in excess of 90% of the Proctor density.

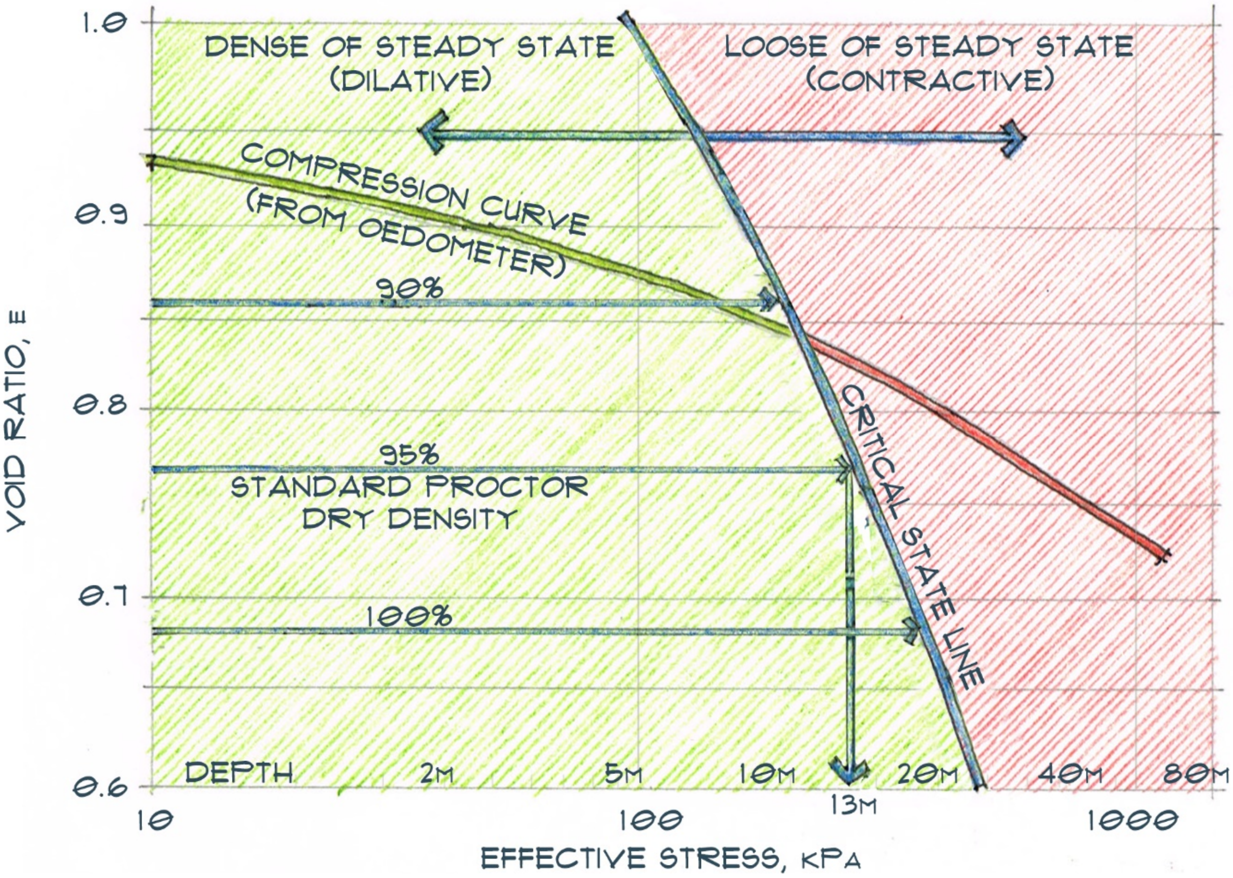

Figure 3 **The density specification for filtered tailings considers the critical-state line. High structures require very dense tailings at the base if dilative behaviour is required**

Second, there are many vagaries in the determination of the steady-state line; often, the only data available prior to construction are for pilot mill tailings from a batch sample that is usually somewhat different from the final grind; the grind is likely to change over time; and the exact location of the dense/loose boundary is a function of sample preparation, saturation, specific gravity, and grain size. Torres-Cruz & Santamarina (2020) provide a framework to assess the critical-state line for tailings and a database of tailings parameters.

Third, tailings grain size and density in the field will vary, particularly during the first months of production and also throughout the facility’s operational life. This can result in some zones being less dense than others but, ideally, should remain considerably denser that the critical-state line. For these reasons, the compaction specification should be determined conservatively and monitored closely. In practice, it will generally be set to at least 95% of standard Proctor dry density, and higher for the lowest layers of a high deposit. The placement moisture content spec is generally only required for ease of compaction, not the long-term performance.

Crystal et al. (2018) describe how high filtered tailings stacks (greater than 20 to 30 m) involve a risk that the lowest-most tailings will change from a dense/dilatant state to a loose/contractive state that is prone to liquefaction (i.e. crossing the critical-state line in Figure 3 at 300 to 600 kPa). Robertson (2017) indicates 'contractive sand-like soils become progressively more ductile with increasing stress'. Many tailings stacks are tens of metres high (e.g. Emerman 2021) and have stresses of several hundred kilopascals or more at the base. Proper design requires addressing the potential for this dilative-to-constrictive phase transfer for all stages of operation and closure (see Smith et al. 2019). Ulrich & Coffin (2017) emphasise the importance of considering a significant shift in the critical-state line for unsaturated conditions.

As an alternative, some designers consider the potential for incorporating loose saturated tailings layers, and therefore design the slopes with adequate factors of safety in the event of liquefaction of any of these layers (e.g. Tetra Tech 2007).

3 Material handling and compaction issues

3.1 Filtered tailings are produced too wet

Filtering is ultimately a consolidation phenomenon. The rate of water release during filtration for a given pressure decreases exponentially with time. Filtration times of minutes to tens of minutes to achieve the moisture specification (often expressed as a minimum percent solids) are commonly reported. As the tailings desaturate, capillary suction reduces the rate of water release. Filtration time is, therefore, a matter of diminishing returns, changing only a fraction of a percentage point for each drying minute (e.g. Wisdom 2020) and affecting throughput rates. The required geotechnical moisture content specification (using the Proctor optimum as a rule of thumb) can be difficult to achieve, particularly if the filter plant is undersized. Confusion between a vendor's aspirational 'target' moisture and a hard geotechnical design specification (Crystal et al. 2018) is not uncommon.

There are often two confounding factors. First, filtered tailings often dewater fairly rapidly to a moisture content that is a few points wet of the Proctor optimum moisture content, and each additional percentage point of moisture content reduction is reached more slowly than the previous one. The filter plant may be undersized and unable to consistently produce tailings to the required specification. Slowing the mill production rate is seldom a realistic option. Changes to the orebody, milling to a finer consistency, or changing the reagents or flocculants over the life of the mine may also lead to increased moisture content at the end of filtration (Lupo & Hall 2010). Final moisture contents are measured by periodically sampling the tailings and drying the sample in an oven. The filter plant and filter stack operators also rely on visual cues, and the behaviour of the tailings as it forms a discharge cone in particular, to assess the moisture content.

One solution is to ensure that the filtration plant is adequately designed, that there is enough filtration time/ filter area/adequate chemical treatments and good monitoring and control to ensure that the tailings are produced on spec. A second solution, discussed below, is to zone the deposit to accommodate wetter tailings in specific zones (there always needs to be somewhere to place the tailings to avoid restricting the mill throughput).

The second confounding factor involves all-too-common confusion in the definition of moisture content. Plant operators and process engineers almost invariably use a definition that differs from the one used by geotechnical specialists. The lack of a shared understanding is often a root cause of tailings being consistently delivered wet of the geotechnical specification. Furthermore, much of the data reported in the literature are ambiguous with regard to which definition is being used. Be specific.

- The mining (process/slurry) water content (w_m) is defined as the ratio of the mass of water (m_w) to the total mass of slurry (mass of water + mass of solids = $m_w + m_s$). The use of mining water content, $m_w/(m_w + m_s)$, is convenient for process control and calculating water budgets, and it is commonly used worldwide for mineral process engineering. In this definition, changes in m_w affect both the numerator and denominator, but not proportionally.

- Conversely, the geotechnical (gravimetric) moisture content (w_g) is defined as the ratio of m_w/m_s. Using this definition, the geotechnical 'moisture content is directly proportional to the mass of the water present' (Liu & Evett 2009). This geotechnical moisture content definition has proven to be a useful predictor of the geotechnical behaviour of soils and is used universally by the geotechnical community.

In equation form, mining water content, m_w is

$$w_m = \frac{m_w}{m_w+m_s}$$

geotechnical moisture content, w_g is

$$w_g = \frac{m_w}{m_s}$$

and to convert from mining water content to geotechnical water content

$$w_g = \frac{w_m}{1-w_m}$$

or to convert from geotechnical water content to mining water content

$$w_m = \frac{w_g}{1+w_g}$$

As shown in Table 1, the geotechnical moisture content is always higher than the mining water content. At values near the Proctor optimum, the two are only a few percentage points different, but this difference is often the culprit, standing between producing tailings that are easy to compact versus tailings that can be impossible to compact. Clear communication is essential.

Table 1 The crucial difference between mining water content and geotechnical moisture content.

Mining solids content $m_s/(m_w + m_s)$	Geotechnical moisture content m_w/m_s	Mining water content $m_w/(m_w + m_s)$
100%	0%	0%
95%	5%	5%
90%	11%	10%
85.5%	**17%**	**14.5%**
83%	20%	17%
81%	23%	19%
79%	27%	21%
77%	30%	23%
75%	33%	25%
50%	100%	50%

3.2 Tailings gain moisture while stockpiled

Tailings to be trucked to a facility are typically discharged from a conveyor to form a cone stockpile to be loaded into a haul truck. If this loading area is exposed to the elements, tailings can pick up rainwater or water puddling on the ground, becoming wetter and more difficult to compact. Therefore, many mines use large, well-ventilated, unheated sheds to protect these temporary stockpiles. Such sheds can also limit the freezing of the tailings (Figure 4). Mines in tropical areas may use a simple roof instead.

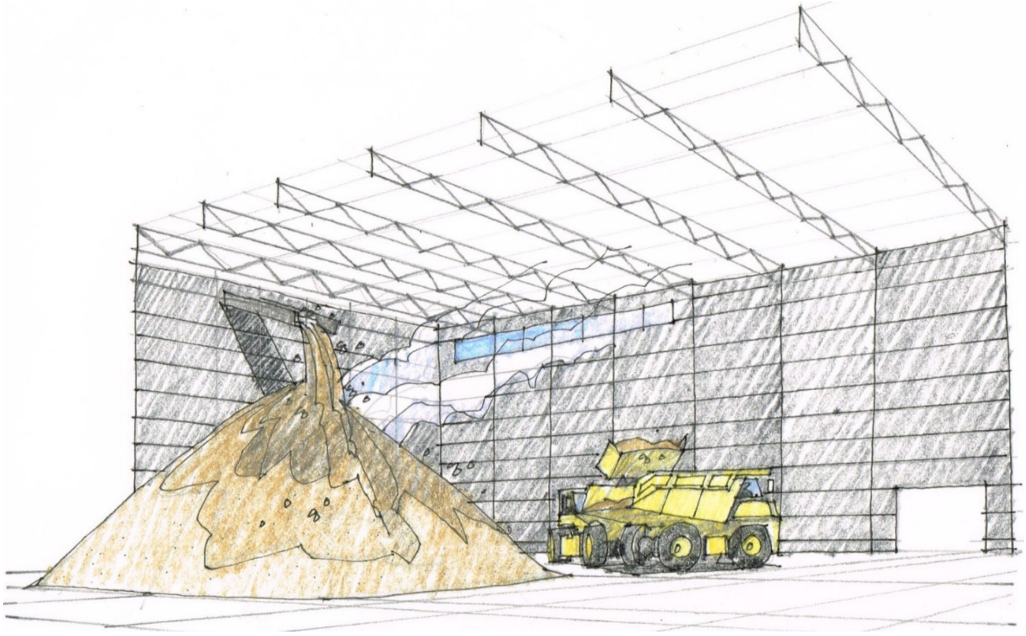

Figure 4 Filtered tailings awaiting trucking is protected from environmental conditions by a large shed

3.3 Tailings freeze before compaction

In cold climates, tailings can freeze before they can be compacted. Even partially frozen tailings will not achieve the compaction specifications, no matter the number of passes of compaction equipment. Perhaps surprisingly, it is not always obvious visually if unsaturated tailings are frozen or not.

Tailings must be kept from freezing during stockpiling, during transit (some mines use heated truck boxes), and in low-temperature conditions, and they must be dumped and spread within minutes to hours before freezing (see Cameron et al. 2001; Davies et al. 2022). Figure 5 shows a typical winter operation. Once the lift is compacted to specification, the design may allow it to freeze, although consideration of the time to thaw may be important to the design and future performance. Frozen layers can impede seepage flow and cause saturation above.

Tailings that freeze before being compacted are removed and either stored until they thaw in the spring, or are moved to a (pre-planned) zone that can safely off-spec tailings. Frozen layers can also inhibit further consolidation and strength gain. The strength when the material eventually thaws will be the same or less (often much less) than the strength at freezing.

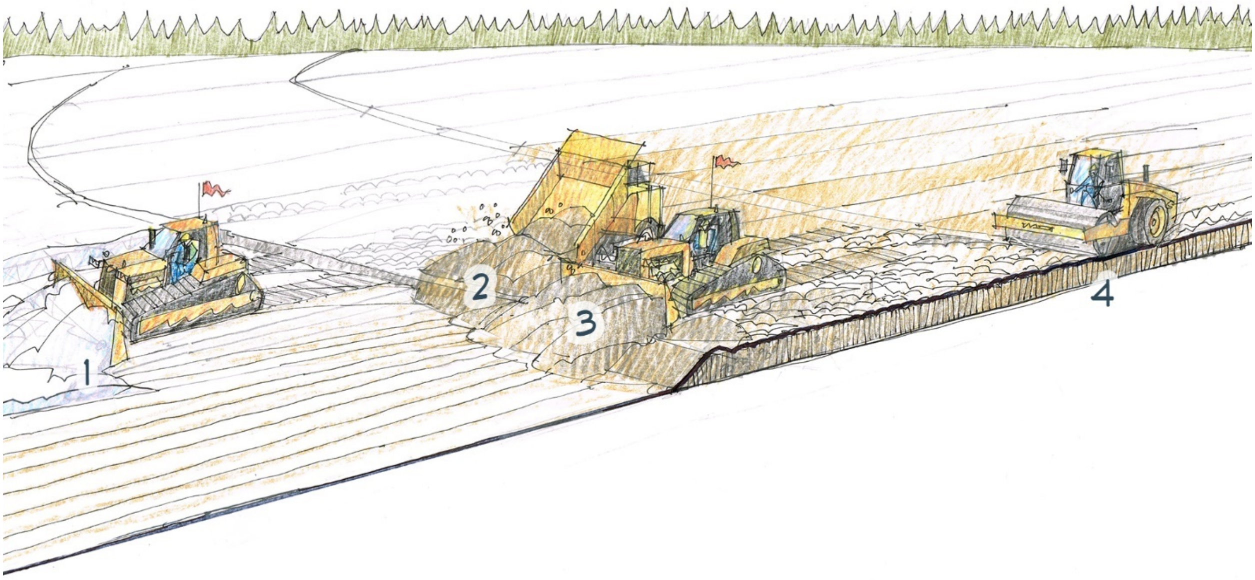

Figure 5 Compacting before freezing (minutes matter in cold conditions)

3.4 Erroneous density readings

Portable nuclear densometers are routinely used in earthworks construction to measure the density and moisture content of compacted materials (see Tripathi et al. 2015). They can typically measure to a depth of 0.3 m. But this indirect measure of density and moisture can sometimes provide erroneous readings, particularly for tailings with high organic/coal content or elevated metals content, especially iron (Boldt 1985).

The use of a nuclear densometer in tailings must be calibrated against a known standard, typically using a sand-cone or water-balloon method, which provides a direct measure of density using a volume replacement method (Figure 6). Some practitioners may use laboratory chamber calibration and a large sample volume compacted to known densities and tested with a nuclear densometer to develop a correlation.

At some sites, differences between actual sand densities and moistures measured with a nuclear densometer are small and consistent and can be corrected in the field for local conditions. At other sites, the errors are so large and/or highly variable that a nuclear densometer cannot be used. In this case the sand-cone or water-balloon method is used (although it is more laborious). Some mines are experimenting with various portable cone penetration methods as a proxy for measured density; these also need to be calibrated with a test fill with direct density measurements. Unlike other methods, the penetration test does not work for frozen or partially frozen tailings. Also, interpreting cone penetration test (CPT) results is complicated when the tailings is only partially saturated, as is predicting future saturated behaviour based on CPT data (e.g. Russell et al. 2010; Yang & Russell 2016).

When uncalibrated, the measured field densities can be misleading, indicating dense tailings when they are in fact loose, which is a common problem.

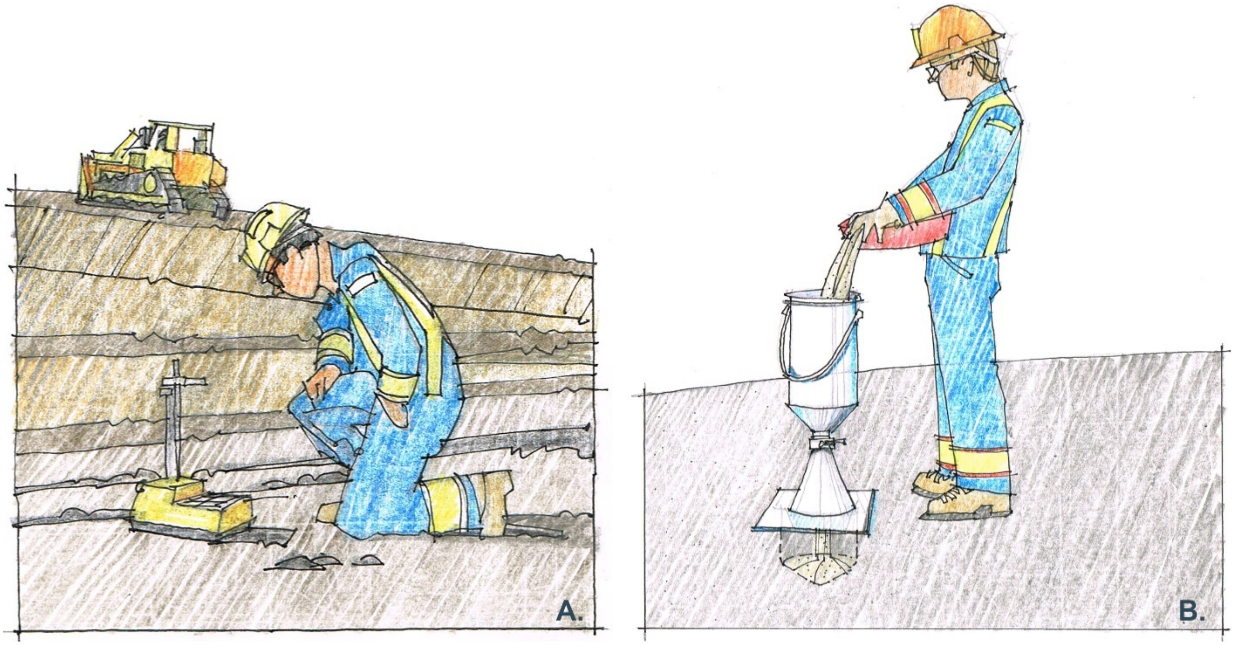

Figure 6 **The nuclear densometer and sand-cone methods of measuring the dry density of a filtered tailings lift**

3.5 Difficulty in employing a compaction method specification

Mines often prefer to develop a method specification for compaction (instead of relying on direct density measurements). Compaction trials are run with specific compaction equipment. The change in the density of each lift is measured with each pass of the equipment. Several different lift heights are typically trialled, with several lifts for each trial. The density of the entire thickness of each lift must be tested, which may require carefully digging shallow test pits through the compacted lift and testing at various depths (making sure the pits are wide enough to avoid 'wall effects' if a nuclear densometer is used). A typical method specification may include such directions as: 'The tailings shall be compacted in lifts 0.3 m thick using four passes of a 10T smooth drum vibratory roller with vibration turned on.' There may be additional rut-and-roll criteria along with criteria for cleaning up between lifts and placement times to avoid freezing. Using a method specification is particularly attractive if the as-delivered filtered tailings have a consistent grain size and moisture, which is often the case. A CPT through the trial lifts can be used to correlate its response with known densities, although the shallow nature of the test requires a large correction to the CPT data and also requires correction for unsaturated zones.

The main difficulties posed by a method specification in daily operation occur when the tailings are allowed to freeze (completely or partially) before compaction. Although compaction will not meet the required specification, this may not be obvious to the operator. The second difficulty occurs when the method specification does not receive adequate quality control. A third difficulty arises when the compaction trial is poorly executed and uncalibrated nuclear density readings employed.

For the engineer of record to certify that the method specification is being used properly and that the tailings is indeed being compacted to an adequate density, there needs to be a quality control process that includes a technical person continually supervising (Figure 7) and documenting the compaction efforts (as well as the lift height, and clean-up status of water, slope, snow, and ice prior to lift placement, among other issues). Periodic checks on lift clean-up and measured density are also necessary. These quality control steps are sometimes overlooked or applied inconsistently.

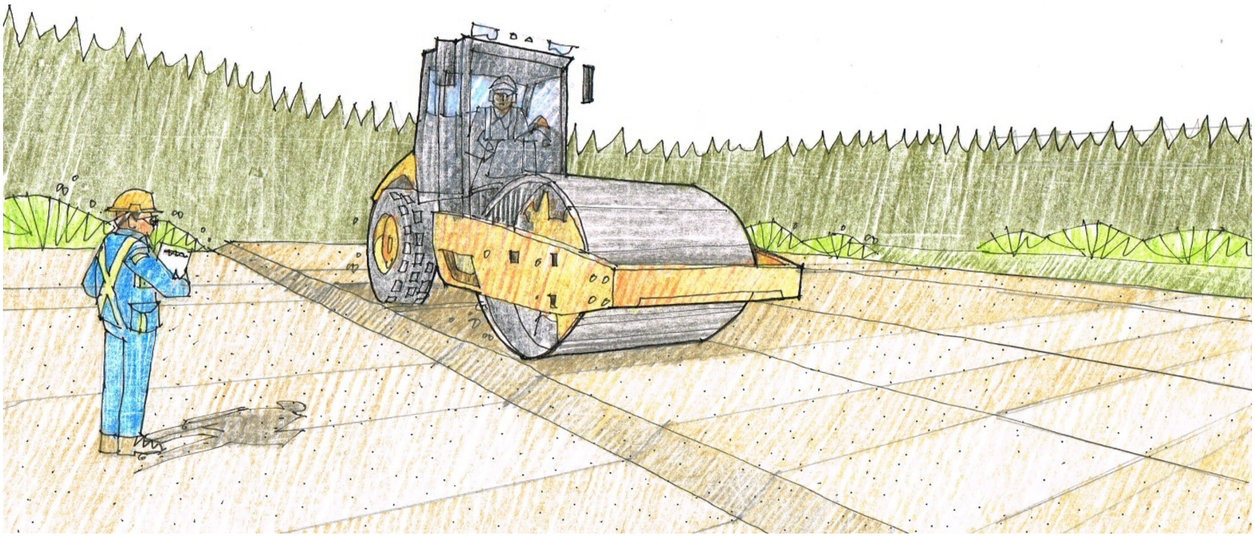

Figure 7 A method specification requires continual observation/quality control by qualified geotechnical personnel

3.6 Keep graded to avoid ponded water

Water may pond on the surface of the filtered tailings stack, which can cause excess percolation and/or rewetting of the tailings, perhaps leading to more rapid resaturation than planned, loss of density upon rewetting, and trafficability issues (Wood 2003; Norwest & M3 2015). Therefore, the lifts are sloped away from the crest to avoid ponded water, directing runoff water to a collection area.

3.7 Inadequate quality control and quality assurance

The need for both a quality control program and a quality assurance program is sometimes overlooked. However, just as in dam or other earthworks construction, it is essential to employ a formal process of quality control that includes routine periodic testing of the grain size and moisture content of the as-received filtered tailings, observation, monitoring, and documenting the compaction on every lift, and testing of the standard Proctor density on a per-volume basis (see Fell et al. 2014 [Table 14.3]).

A quality assurance program typically (Figure 8) involves periodic oversight from the engineer of record to ensure that adequate laboratory and field testing is being carried out, that the procedures are correctly and consistently followed, and that all people involved are qualified. This includes periodic site inspections in different weather conditions, and possibly an annual CPT program to confirm that the compaction requirements have been met. Lemieux et al. (2011) provide an example of a CPT program and analysis applicable to a tailings quality assurance program. The quality assurance program may also need to retest the critical-state line of reconstituted (or undisturbed field samples), especially if there is a change in milling, filtration, or the produced grain size/geochemistry. Such advanced laboratory testing, while specialised, is now routine in the industry.

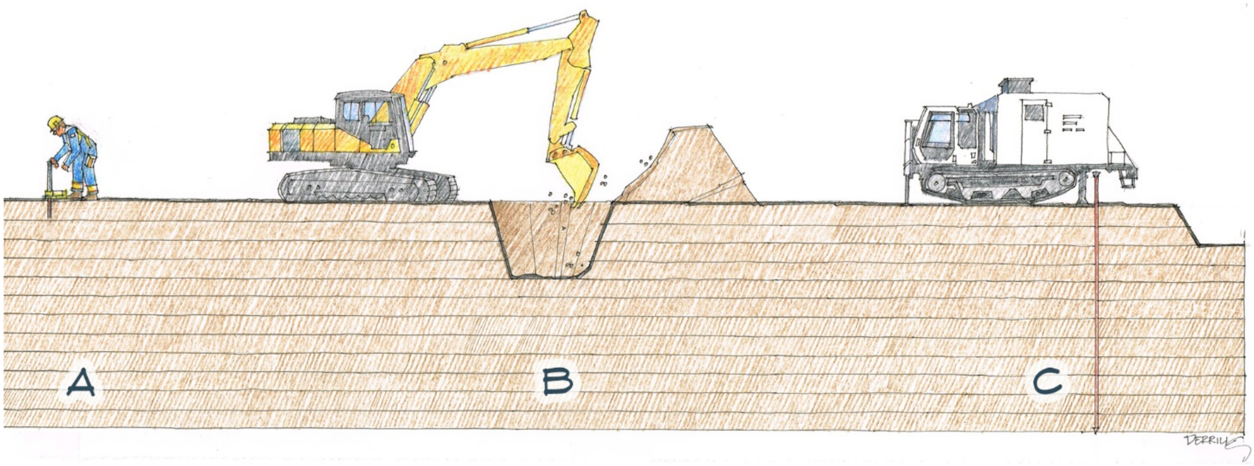

Figure 8 **Some methods of quality control (QC) and quality assurance (QA) for filtered tailings compaction: (a) Point density; (b) Test pitting and sampling through lifts; (c) CPT testing**

3.8 Saturation at the base of the stack or along layers

Filtered tailings stacks are often designed such that the tailings remain less than about 85% saturated to reduce the risk of liquefaction. However, a saturated layer may form at the base of the pile (or along any layer with a permeability contrast) due to any combination of the following:

- Excessive volumes of wet off-spec tailings (Ulrich & Coffin 2013).
- Excessive net percolation of precipitation during operations or after closure (Shaw & Ayres 2014).
- Blockage of the underdrain.
- Resaturation of the tailings due to consolidation from increases in stresses (Lupo & Hall 2010).
- Capillary rise above the drainage layer, which may reach several metres for fine-grained tailings.
- Contrasts in permeability of individual layers within the stack that impede water flow.

The lowest layers of tailings are usually the most difficult to place (they are constructed during the commissioning of the mill, of the filter plant, and of the tailings stack), and they are under the highest stress, which can cause resaturation and a phase transition from dense to loose.

Typically, piezometers are installed during construction to monitor porewater pressures within the underdrain layer, slightly above the drainage layer, and within the stack. If vibrating wire piezometers are employed, the leads can be trenched out to the downstream face to make reading and construction easier and safer. The annual CPT program can look for evidence of saturated layers. It may be prudent to ensure that the design can accommodate some saturated layers. Ulrich & Coffin (2013) provide an example of substantial porewater pressures in a filter stack due to tailings moistures exceeding the design specification.

3.9 Poor seepage quality

If the filtered tailings stack has good controls to limit groundwater-influx and good run-on controls, seepage flows from the underdrain will typically be small and perhaps negligible, particularly during the long wet-up period (Davies et al. 2022). However, unsaturated filtered tailings still contain considerable volumes of process water (as porewater) during placement, and ongoing geochemical reactions may generate additional mass loading. The result is that seepage water from the underdrain/toe drains may not meet groundwater or surface water discharge requirements. Filtered tailings are often finely enough grained to limit oxygen ingress beyond a few tens of centimetres of the surface, limiting geochemical reaction rates. Shaw & Ayres (2014) provide a case history of design with insight into the geochemistry, depth of oxidation, and closure of a proposed filtered tailings stack.

To manage these concerns, some operators process their tailings to remove sulphides. High levels of compaction are used to limit net percolation, oxygen ingress, and drawdown rates/discharges. Covers can also be used to limit the net percolation and oxygen ingress into filtered tailings stacks (INAP 2017). Collection and treatment of leachate waters may be required. The fine-grained nature of many filtered tailings stacks may itself limit oxygen ingress beyond a few tens of centimetres, limiting the rate of acidification of tailings which may limit metal loading – limiting the duty of a cover to protecting against erosion and providing a growth medium (see MEND 2012) and perhaps negating a need for a liner. Some mines consider using temporary membrane-type covers (like those used to protect sports field turf from rain) to minimise resaturation during operation. If water fluxes are low enough and water quality high enough, there may be an opportunity for direct discharge to the environment, or for use of semi-passive wetlands (e.g. Pat-Espadas et al. 2018) to manage long-term water treatment for filtered tailings stacks.

4 Summary – how to compact filtered tailings

To reliably compact filtered tailings:

- Recognise that compacting filtered tailings is not always easy, but that good design and operation and close monitoring can make it routine at any site.
- Ensure that the filter plant can reliably deliver a consistent filtered tailings product that is close to the optimum geotechnical moisture content. Mind the definitions of process water content and the geotechnical moisture content. Monitor closely and observe the field performance.
- In harsh climates, build a large enclosure around the filter tailings plant discharge point to protect the tailings from the elements until they can be transported to the stack.
- Ensure tailings remain at a suitable moisture content and unfrozen at least until compacted.
- Develop a reliable and efficient method to monitor as-compacted dry densities. Don’t assume that the nuclear densometer is providing reliable numbers. Test the method periodically. Establish both a QC program and an independent QA program. If using a method spec, ensure it is closely monitored and checked.
- Use piezometers to check for saturation within the stack, particularly in the underdrain and the layer immediately above.
- Plan for closure of the filtered tailings as a landform – place the filtered tailings to allow minimal regrading, easy placement of a cover, and control of surface drainage. In addition, ensure the underdrain is robust.
- Take steps to avoid excess quantities of seepage water of poor quality. Plan to collect and test the water, and treat if necessary, until suitable for release to a semi-passive treatment wetland or directly to the environment.

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References

Access Consulting Group (Access) 2003, *Examination of revegetation methodologies for dry stack tailings in northern environments*, Consultant’s report for the Mining Environmental Research Group, Government of Yukon, Access Consulting Group, 35 p.

Andrews, J, Crouse, P, Henderson, M, McKenna, G, Slingerland, N, Williams, D & Fine Morrison, K 2022, ‘Chapter 15: Closure planning and landform design’, in K Finke Morrison (ed.), *SME Tailings Management Handbook: A Life Cycle Approach,* Society for Mining, Metallurgy & Exploration, Englewood, 1004 p.

ASTM 2021, *Standard test methods for laboratory compaction characteristics of soil using standard effort, ASTM D698–12(2021),* ASTM International (Standard Proctor Dry Density).

Boldt CMK 1985, *Compaction criteria for metal and nonmetal tailings*, Bureau of Mines Report of Investigations 8921, 32 p.

Burnett, A & McKenna, G 2022, 'Celebrating 50 years: the Syncrude Geotechnical Review Board', presented at CDA Canadian Dam Association Conference, St Johns, 20 p.

Cameron, C, Mimura, W, Fong, V & Lussier, L 2001, 'Detailed construction procedures and considerations in Syncrude's quasi-homogeneous earthfill dams', *Proceedings of the 54th Canadian Geotechnical Conference*, Calgary, pp. 235–243.

Condon, PD & Lear, KG 2006, 'Geochemical and geotechnical characteristics of filter-pressed tailings at the Greens Creek Mine, Admiralty Island, Alaska', *Proceedings of the 7th International Conference on Acid Rock Drainage (ICARD),* American Society of Mining and Reclamation (ASMR), Lexington, pp. 350–363.

Crystal, C, Hore, C & Ezama, I 2018, 'Filter-pressed dry stacking: design considerations based on practical experience', *Proceedings of the 22nd International Conference on Tailings and Mine Waste 2018*, Colorado State University, pp. 209–220.

CTMC 2012, *Oil sands tailings technology deployment roadmap: Project Report – Volume 2, Component 1 Results*, Consortium of Tailings Management Consultants, Consultants report to Alberta Innovates – Energy and Environment Solutions, June 22, 2012, 112 p.

Davies, M 2011, 'Filtered dry stacked tailings – the fundamentals', *Proceedings of the Tailings and Mine Waste Conference 2011*, University of British Columbia, 9 p.

Davies, M, Mayhew, K & Anderson, C 2022, 'Chapter 6: Dewatered tailings', in K Finke Morrison (ed.), *SME Tailings Management Handbook: a Life Cycle Approach,* Society for Mining, Metallurgy & Exploration, Englewood, 1004 p.

Davies, MP & Rice, S 2001, 'Alternative to conventional tailing management – 'dry stack' filtered tailings', *Proceedings of the Tailings and Mine Waste Conference 2001*, AA Balkema Publishers, 10 p.

Emerman, SH 2021, *Evaluation of the tailings storage facility for the proposed Savannah Lithium Barroso Mine, Northern Portugal*, Consultant's report to Povo e Natureza do Barroso dated June 29, Malach Consulting, Spanish Fork, UT, 43 p.

Fell, RF, MacGregor, P, Stapledon, D, Bell, G & Foster, M 2014, *Geotechnical Engineering of Dams*, 2nd edn, CRC Press, London, 1382 p.

Hore, C 2020, 'A step change in dry stack tailings – our challenge', *Austmine Water & Waste Management* eBook, 3 p.

ICOLD 2022, *Tailings Dam Safety*, Draft dated November 16, 2022, Committee L Tailings Dams and Waste Lagoons, International Commission on Large Dams, Paris, 210 p.

INAP 2017, *Global Cover Systems Design – Technical Guidance Document*, International Network for Acid Prevention, Consultant's report by O'Kane Consultants, Saskatoon, 216 p.

LDI 2021, 'Mining with the end in mind: Landform design for sustainable mining', Position Paper 2021–01, March 2021, Landform Design Institute, Delta, BC, Canada, 78 p.

Lemieux, N, Leahy, D, St-Laurent, J-F & James, M 2011, 'A case study: The seismic stability of an upstream-raised tailings impoundment (part i)', *Pan-AM CGS Geotechnical Conference*, 8 p.

Liu, C & Evett, JB 2009, *Soil Properties: Testing, Measurement and Evaluation*, 6th edn, Pearson Prentice Hall, Columbus, 440 p.

Lupo, J & Hall, J 2010 'Dry stack tailings – design considerations', *Proceedings Fourteenth International Conference on Tailings and Mine Waste*, A.A. Balkema, Rotterdam, pp. 327–334.

MEND 2012, *Cold regions cover system design technical guidance document, MEND Report 1.61.5c*, Consultant's report prepared by O'Kane Consultants for Mine Environment Neutral Drainage Program, July 2012, 177 p.

MEND 2017, *Study of tailings management technologies*, Consultant's report to the Mine Environmental Neutral Drainage Project by Klohn Crippen Berger, 164 p.

Moore, E 2015, 'After Mount Polley, miners and engineers grapple with the risk of maintain the status quo', *CIM Magazine*, Nov.

Norwest, & M3 2015, *Ajax Project, Tailings disposal best available technology assessment*, Consultant's report prepared for KGHM, Norwest Corporation & M3 Engineering & Technology Corp, 57 p.

Pat-Espadas, AM, Portales, RL, Amabilis-Sosa, LE, Gómez, G, & Vidal, G 2018, 'Review of constructed wetlands for acid mine drainage treatment', *Water*, vol. 10, 25 p.

Proctor, RR 1933, 'The design and construction of rolled earth dams', *Engineering News-Record III*, August 31, September 7, 21, & 28.

Robertson, PK 2017, 'Evaluation of Flow Liquefaction: influence of high stresses', *Third International Conference on Performance Based Design in Earthquake Geotechnical Engineering*, Vancouver, 8 p.

Russell, AR, Pournaghiazar, M & Khalili, N 2010, 'Interpreting CPT results in unsaturated sands', *2nd International Symposium on Cone Penetration Testing*, Huntington Beach, CA, 8 p.

Shaw, S & Ayres, B 2014, *Geochemistry, seepage, and closure considerations for dry stack tailings facilities*, NATCL Public Hearing Presentation, December 2–4, North American Tungsten Corporation.

Smith, K, Fanni, R, Chapman, P & Reid, D 2019, 'Critical state testing of tailings: comparison between various tailings and implications for design', *Proceedings of Tailings and Mine Waste 2019*, University of British Columbia, pp. 1183–1195.

Tetra Tech 2007, *Dry tailings facility design: Rosemont Copper*, Consultant's report to Augusta Resource Corporation, Tetra Tech, Golden, CO, 159 p.

Torres-Cruz, LA & Santamarina, JC 2020, 'The critical state line of nonplastic tailings', *Canadian Geotechnical Journal*, vol. 57, pp. 1508–1517.

Tripathi, B, Makwana, P & Kumar, R 2015, 'Study of nuclear density gauge for compaction measure', *Comparative study of conventional methods with NDG for compaction measure*, Lambert Academic Publishing, 86 p.

UBC 2021, 'Myths and Realities of Tailings Dewatering Workshop', by The Normal B Keevil Institute of Mining Engineer, University of British Columbia, presented at Tailings 2021: 7th International Conference on Tailings Management, 110 p.

Ulrich, B & Coffin, J 2013, 'Considerations for tailings facility design and operation using filtered tailings', *Paste 2013: Proceedings of the 16th International Seminar on Paste and Thickened Tailings*, Belo Horizonte, PowerPoint slides.

Ulrich, BF & Coffin, JG 2017, 'Characterization of unsaturated tailings & its effects on liquefaction', *Tailings and Mine Waste 2017*, University of Alberta, Edmonton, 10 p.

Vargas, CC & Campomanes, P 2022, 'Practical experience of filtered tailings technology in Chile and Peru: an environmentally friendly solution', *Minerals 2022*, vol. 12, no. 7, 64 p.

Wisdom, T 2020, 'FLSmidth filtration for tailings management', viewed 23 December 2022, 66 p, https://www.dosso.cl/fm_weblogin/pdf/4-filtered.pdf

Wood, RK 2003, *Response of dense beach above water tailings to cyclic equipment loading at Syncrude's Southwest Sand Storage Facility*, MSc thesis, University of Alberta, Department of Civil and Environmental Engineering, Edmonton, 223 p.

Yang, H & Russell, A 2016, 'The cone penetration test in unsaturated silty sands', E-UNSAT: E3S Web Of Conferences 9, 6 p.