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A comparison of alternative tailings disposal methods — the promises and realities

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Abstract

Despite technological advances in mineral processing, mining companies still face challenges in how to best manage tailings materials. In addition, mining of lower grades of ore has resulted in increased water use per unit of production; at certain sites, water availability is the single greatest constraint on mine development. In some cases, alternative tailings disposal (ATD) has been viewed as a 'silver bullet' that will address all tailings management issues, especially water concerns. In addition, in some cases ATD technologies also promise a smaller footprint and reduced environmental impact and risks.

This paper looks at the promise and realities of ATD methods and will provide high-level guidance on when to use individual technologies and where conventional wet disposal is still the preferred method. The various tailings disposal types presented are filtered, paste, thickened, and conventional disposal.

Energy supply, climate, production rates, project economics, operational predictability, topography, seismicity, and water are used to frame the benefits and limiting factors behind each ATD method. Recommendations on when to use each disposal method are made.

1 Introduction

As the world population grows, society's need for metals grows, and as supplies of metals diminish, mining companies around the world are willing to consider mining ever lower grades of ore. This has led to increased water consumption at mines. In need of answers, the mining industry is looking to alternative tailings disposal (ATD) methods to help conserve water. In some cases, ATD methods have been viewed as a 'silver bullet' that will address all tailings management issues, especially water concerns (Jewell, 2006). In addition, in some cases ATD technologies also promise a smaller footprint, reduced environmental impact and fewer risks. This paper discusses the different types of tailings disposal methods, their promise and what each method actually delivers.

2 Definition of terms

Tailings materials are the residue from a hydrometallurgical process in the mill for the recovery of precious metals, industrial metals, diamonds, uranium, or other materials. Tailings materials are discharged as a slurry from the mill with particle-size distribution and chemistry being dictated by the mineralogy of the orebody and the recovery process used. The definitions of conventional, thickened, paste, and filtered tailings disposal are highly variable. For the purposes of this paper, and in order to maintain consistency, the following definitions will be used in this paper:

- Filtered tailings disposal: involves removal of water by vacuum or pressure methods. Tailings are 'dewatered' using drum, disc, or belt filters (by vacuum) or with filter presses or belt press filters (using pressure) to slurry densities greater than 85% solids by weight. The 'dry cake' or 'filter cake' material requires transportation by truck or conveyor.

- Paste tailings disposal: involves dewatering the tailings material in specialised paste thickeners, or ultra-high-density thickeners, to achieve a slurry density that is still pumpable. Target slurry densities for paste thickeners are generally between 70 and 85% solids by weight. Positive-displacement pumps or similar equipment are required to transport the slurry. Centrifugal pumps may be able to pump up to a yield stress of about 200 Pa (Boger et al., 2006).
- Thickened tailings disposal: involves producing a tailings slurry that tends not to segregate upon placement, using high-density or deep-cone thickeners. Slurry densities of thickened tailings generally range from 50 to 70% solids by weight. The thickened slurry can be pumped using centrifugal pumps.
- Conventional tailings disposal: involves discharging the tailings slurry from the mill at a solid content between 25 to 45% solids by weight. Conventional tailings can also refer to the tailings slurry produced in shallow thickeners. Generally, these slurry densities are on the order of 30 to 55% solids by weight, recovering some water for reuse in the mill but discharging the slurry at the density for most efficient conveyance to the disposal site. As a result, the conventional method is currently the most common tailings disposal method used at mine sites.
- Thickening: the term thickening in this document refers to use of high-rate (shallow, conventional), high-density (deep-cone), or ultra-high-density (paste) thickeners.
- Dewatering: dewatering refers to activity employing high-rate (shallow, conventional), high-density (deep-cone), ultra-high-density (paste) thickeners, or filtration (all types) to remove water and produce a slurry with a higher solid content.
- Slurry: a slurry refers to a tailings suspension or mixture regardless of solids content or dewatering method.
- Tailings storage facility (TSF): tailings materials are stored in impoundments (tailings ponds) created by embankments that can be constructed from excavated earth or rockfill, tailings material, and/or waste rock. The embankments and impoundments are referred to as tailings storage facilities (TSF).

The percent solids values listed in the definitions above are general reference values for comparison of disposal methods only. The actual rheological behaviour of the tailings (based on yield stress, clay mineralogy, and other factors) dictates the selection and effectiveness of the various methods of tailings handling and disposal. The range of tailings disposal methods (from conventional slurries to various ATD applications) can be grouped into the following general categories, based on these other factors.

Table 1 Summary comparison of conventional and ATD

	Typical Incoming % Solids	Typical Outgoing % Solids[1,4,5]	Typical Yield Stress, Ty, (Pa)	Typical Angle of Deposition (%)	Typical Slump (mm)[2]	Typical Water Content (% dry mass basis)	Typical Percent Water Recovery[3]
Conventional Tailings Disposal	25–45	30–55	10–100	0.5–2.0	NA	100–400	50–60
ATD Thickened Tailings Disposal	30–45	50–70	10–300	1.0–3.0	NA	30–100	60–70
ATD Paste Tailings Disposal	60–65	70–85	100–1,000	3.0–10.0	200–275	20–30	80–90
ATD Filtered Tailings Disposal	60–65	> 70	> 1,000	NA	NA	10–20	> 90

[1, 3] (Bussiere, 2004); [2] (Newman, et.al., 2001); [4] The dry solid content obtained depends mainly on the geotechnical properties of the material and possible pre-treatment (e.g. separation). In general it can be stated that the finer the material the more need for ATD; [5] From MWH project experience.

3 So why isn't everyone doing it?

Despite the perceived advantages, there are a number of factors that determine whether an ATD technology is suitable. Some of the factors that influence the use of ATD technologies include:

- Energy supply: removing water from a slurry requires energy. In addition, unless the mine's TSF is downhill from the mill, transporting filtered, thickened, or paste tailings materials will likely require more energy to transport than a conventional slurry. The location of the tailings material process equipment in relation to the discharge area can therefore have a large influence on the energy consumption. With increased energy, expenditure comes with additional costs. Some mines that have an expensive or restricted energy sources may not find ATD beneficial.
- Climate: the successful desiccation of filtered, thickened and paste tailings material is aided by a dry climate. Successful implementation of filtered and thickened tailings disposal methods are often seen in dry climates.
- Production rates: although the industry is seeing technological advances, filtered and paste technologies are unproven at mines with moderate (30–50K tonnes/day (t/d)) to high production rates (>100K t/d). While thickened technologies are sometimes used at mines with moderate production rates, conventional tailings deposition remains the only proven technology at mines with high production rates.
- Project economics: mine operators must weigh the tradeoffs that come with using an ATD method: a reduced footprint and less water used come at the expense of higher initial capital. While operating costs to create a thickened, paste or filtered tailings are likely higher, these costs maybe off-set by savings in other areas, such as the opportunity to forego building a large tailings dam. Of the numerous ATD cost comparison studies performed by MWH to date at sites in the Americas, all have shown ATD methods to be more expensive than conventional disposal (MWH, 2009). Despite

this experience, it is not possible to make a blanket statement as to the costs to implement ATD technologies, as they are highly site specific.

- Operational predictability: maintaining uniform deposition slopes on paste and thickened disposal facilities has proven to be a challenge because of fluctuations in ore characteristics, tailings gradations and percent solids. In the case of filtered technology, for example, coordinating the material handling, spreading and compaction at a high production rate and with variable weather conditions is not a simple task. Further, ATD technologies are equipment intensive: high-density thickeners, filter presses, conveyors, and specialty piping are all fallible and may limit operational stability. Mines operating under narrow production constraints may be prohibited from employing ATD technologies because of the possibility of operational instability. Some operators prefer to optimise the milling and metal recovery operation, sacrificing performance of the tailings disposal system. In some cases conventional tailings disposal facilities may be required with ATD technologies.
- Topography: some ATD technologies (e.g. thickened and paste) lend themselves to flat topographies and are usually not feasible (without embankment support) at sites with even moderately steep terrain. Filtered tailings disposal can be implemented in a variety of terrains provided stability, operational and closure requirements are taken into account.
- Seismicity: mitigation measures to address concerns about dynamic stability of slopes with tailings processed with ATD technologies may negate many of the perceived benefits.
- Water: the needs to conserve and reuse water are two of the main drivers behind the implementation of the ATD technologies. The filtered technology saves significant amounts of water; paste technology also saves water, although not as much. In many cases, the water saved by the thickened technology is only marginally better than conventional disposal, see Table 1.

4 Filtered tailings disposal

4.1 The promise

The driver for implementing the filtered tailings disposal method is often related to one of the following:

- Improved water conservation: a limited water supply is an important driver for tailings filtration as it can help maximise water conservation and water recycling.
- Space conservation: because filtered tailings materials are stockpiled at a higher dry solid content (tons dry matter/m^3 (tDM/m^3)), they have a much smaller footprint than conventional tailings disposal.
- Reduced environmental risks: environmental risks including the potential for impact to the groundwater and embankments/dam/ dikes failure are much lower with filtered tailings disposal provided they can be compacted to densities that would avoid liquefaction under seismic loading. Because filtered tailings materials have good geotechnical properties and low permeability, they therefore present fewer environmental risks.
- Improved compliance: environmental regulations have become more stringent, this increased scrutiny is influencing mining companies' decisions towards filtered tailings disposal.
- Better handling in cold conditions: cold conditions can make water handling difficult and filtered tailings disposal attractive.
- Fewer topographic limitations: topographic limitations can limit the feasibility of conventional tailings disposal.

4.2 The nuts and bolts

The water phase of the slurry is either pushed through the filter under pressure or pulled through the filter by vacuum pressure. The types and configurations of filters vary widely; each has its own method of filtration and its own discharge and transport methods for cake and filtrate. Tests on filtration and geotechnical properties of the material are needed to determine specific process parameters. The different filtration techniques (vacuum and pressure filtration) are outlined below.

Vacuum filtration uses a vacuum supplied by a drop leg or motorised vacuum pump to draw the liquid out of the slurry. The three main categories are drum, disc, and horizontal belt filters.

Pressure filtration uses hydraulic or mechanical devices to secure the pressure to expel liquid from the slurry. The major categories include batch filter presses and belt press filters.

Using hydrocylcones to separate materials by particle size (generally set at 63 µm) can allow the filtration installation to be designed for a lower capacity. This technique is commonly applied in design of filtered tailings installations. The coarse fraction can be drained by gravity using dewatering screens.

Table 2 shows different aspects of the filtration techniques outlined above.

Table 2 Different aspects of filtration techniques

Type	Process	Conditioning	Heavy Duty	Max. Solids Content[1]	Electricity Consumption[2]	Critical Design Parameters
Vacuum Filtration						
Belt filter	Continuous	Case by case basis[5]	Yes	>75%		Belt speed Layer thickness
Disc filter	Continuous	Case by case basis[5]	Limited[3]	>70%	High	Rotation speed Layer thickness
Drum filter	Continuous	Case by case basis[5]	Limited[3]	>70%		Rotation speed Layer thickness
Pressure Filtration						
Chamber filter press	Batch[4]	Case by case basis[5]	Yes	>75%		Cycle time Dry matter content
Membrane filter press	Batch[4]	Case by case basis[5]	Yes	>85%	Low	Cycle time Dry matter content
Belt press	Continuous	Polymer	Limited[3]	>70%		Belt speed Layer thickness

[1] The dry matter content that can be obtained is highly depending on the specific gravity of the material as well as other material characteristics. The numbers in this table are therefore only indicative considering mining default values.

[2] This conclusion was drawn out of a feasibility study conducted by MWH that compared dewatering of tailings using horizontal belt filters or membrane filter presses for a specific case.

[3] In general, rolling devices result in higher maintenance requirements of the installation.

[4] If different filter presses are installed, the overall process of dewatering by different units of filter presses can be seen as a continuous process.

[5] Conditioning with lime and/or polymer can be done to improve dewatering properties of the sludge depending on its characteristics. However it is not required.

As shown in Table 2, vacuum filtration as well as belt press filtration, are continuous processes resulting in less buffer capacity requirements. Although some techniques (e.g. belt press filters) require standard addition of chemicals, conditioning generally relies on the desired product properties after dewatering. Often, conditioning results in higher solids content after dewatering. Selection of filtration technique can therefore be influenced by conditioning requirements when taking into account environmental issues as well as economic aspects.

The highest solid content is obtained using filter presses, resulting in the highest corresponding water recovery. The high solids content also brings along improved geotechnical properties. Compacted and stacked filter cakes have been constructed at slopes up to 22° or 2.5H:1V for non-ferro goethite sludge (Foged and Vandekeybus, 2006). However, experience has indicated that even slight differences in solids content can have a large influence on the geotechnical properties and handling properties of the filter cakes. Also, specific seismic risks play a major role in determining the maximum slopes of the dikes. As a result, in some cases it is worthwhile to investigate the use of the dewatered material as construction material for the dikes; as this makes construction of additional dikes subordinate. This can be investigated in geotechnical tests simulating relevant seismic conditions. Electricity consumption is considered to be generally higher for vacuum systems compared to pressure systems. The process building dimensions are larger for filter presses compared to the other techniques described in Table 2. In general, belt presses are used less often for tailings filtration due to high operating and maintenance costs. Vacuum belt filtration is a common technique used for filtration of tailings materials, but filter presses generally give the best results for solids content and geotechnical properties.

As filtered tailings are generally unsaturated, stacks are susceptible to oxidation. If the filtered tailings are acid generating, the oxidation process can result in acid generation and drainage.

4.3 The reality

Examples of applications of the above mentioned techniques are summarised in Table 3. The examples are not only related to filtered tailings, as filtration techniques have proven their benefits for dewatering different process flows. It is important to note that the first two examples (ore processing and harbour sludge dewatering) described in the table involve installations for dewatering of fine materials with geotechnical characteristics that differ from those of most tailings materials. Filtration efficiency of these materials is generally lower than that of tailings materials, resulting in higher filtration pressures, longer cycle times and lower solids contents of the filter cakes. Using the same installations as described in these two examples for tailings filtration can therefore result in a multiplication of the capacity by a factor of four or even more, depending on the geotechnical properties of the tailing.

Table 3 Summary of operating filtered tailings disposal facilities

Where	What	Material	Production Rate (tpd)	Dry Solids Content (%)	Filtering Type
Balen, Belgium	Ore processing plant	Zinc	470	60%*	2 membrane filter presses each having a filtration area of 1,240 m^3/press
Antwerp, Belgium	Harbour sludge dewatering plant	–	2,500	65%**	12 membrane filter presses each having a filtration area of 1,240 m^3/press
Confidential	Mine	Gold and silver	15,000	75–80%	12 horizontal belt filters***
Confidential	Mine	Copper, iron and sulfur	10,000	82%	2 horizontal belt filters

* To optimise the efficiency of the filtration process, filtration is being performed up to a dry solid content of around 60%. This percentage is lower than the dry solid content generally obtained for filtered tailings due to different geotechnical properties of the goethite sludge when compared to tailings materials. Through the conceptual and detailed design of a filtered tailings process, the tailings pond lifetime increased from 6 ½ to 22 years, while dramatically reducing the environmental impacts and safety risks at the site.

** The dredged sludge has a specific gravity of 2.65 t/m³. The filter cakes of the mineral harbour sludge are characterised by a water content that is high compared to water contents of filtered tailings materials due to its high clay contents. However, geotechnical properties of the filter cakes are very good. Cohesion is determined to be 28 kPa and angle of internal friction is 34°.

***Initially, the thickened tailings were placed directly on the filter belt; however, belts became clogged by fines, and maintenance costs were significant. Therefore, the thickened tailings are now hydrocycloned to separate the coarse fraction from the fine fraction prior to filtration. The coarse fraction is placed directly on the filter belts, and the fine fraction is placed on top of the coarse material. The coarse material serves as a secondary filter for the fines.

4.4 Application

The potential for water recovery, the limitation of long term environmental impacts, and the opportunity for space conservation makes filtered tailings disposal a very attractive disposal option. Filtered technology allows mine operators to forego costs associated with construction of tailings impoundments, reduce the space needed for tailings storage, and limit the amount of required make-up water, since filtering allows much of the water to be recycled to the process.

Under a growing number of site and regulatory conditions, filtered tailings disposal offers a sustainable alternative to manage tailings materials in a manner that addresses many concerns of the mining industry, its regulators, and the public in general. In addition, in areas where seismic risk is considerable, reduced liquefaction potential from filtered tailings material is considered a real environmental advantage.

The cost of equipment, operation and maintenance make filtered tailings disposal operations more expensive per tonne of tailings than conventional slurry disposal. However, some filtering costs can be offset by improved storage efficiency and smaller environmental impacts. The costs of moving tailings materials to the disposal site impoundment are generally higher than conventional slurry transport. This is one of the main reasons why filter installations are preferably built close to the stacking area. In addition, although overall water losses are minor, provisions must still be made for controlling seepage to groundwater. Although dust generation is an issue for most filtered tailings facilities, it can be managed by keeping the active placement area small.

Selection of one of the filtration techniques described above depends mainly on the specific boundary conditions and do’s and don’ts of the tailings disposal facility. Site-specific testing and analyses are required to characterise the dynamic performance and specific requirements for ‘dry stacks’.

Over the past five years, filtered tailings disposal has become increasingly common. The advantages of filtered tailings disposal are most apparent for sites in arid, highly seismic or cold regions, or where space is limited or where meeting environmental regulations through the use of a conventional tailings disposal is difficult.

Currently, the maximum throughput of a filtered tailings facility is estimated to be around 20,000 tpd. However, much higher production rate operations are in the planning and design stage. For this disposal method to gain widespread use within the industry, it will have to prove scalable and cost efficient for high production rates at large mines.

5 Paste tailings disposal

5.1 The promise

By removing a considerable portion of the water from a slurry, one can change its behaviour from that of a fluid best described by Newtonian physics to a non–segregating paste. Paste has certain properties that have made it useful in mining, particularly where underground mining methods require backfill and hydraulic placement is possible. When a portion of coarse aggregate and/or cement is added, the paste serves as a mortar with predictable structural properties and can be cheaper than a comparable manufactured backfill. The added benefit is reduced environmental impact, as a result of disturbing less land (Tacey and Hart, 2006).

In the context of this paper, the apparent benefits of applying paste technology to tailings for surface disposal include the absence of segregation, limited consolidation and associated seepage and elimination of the need for a reclaim pond. When the geometry of the disposal area is favourable, a containment dike of limited height is required. The ideal would be when the tailings materials have low residual moisture content and very low permeability, so that the water contained at the time of placement remains in place, limiting seepage and the ingress of water at the surface. The material, remaining partially saturated, is therefore potentially resistant to the effects of oxidation and therefore may not yield further environmental impacts. When the paste has some strength (represented by yield stress) and will maintain a slope, storage can be more efficient as a steeper beach slope may result in a smaller embankment. The lower moisture content may also result in a higher in–place density, further improving the efficiency of the storage facility. Where geotechnical or chemical considerations are a concern, if the moisture content is low enough to allow addition of cement prior to disposal, some constituents will be immobilised and the material strength improved (Cincilla et al., 1997).

5.2 The nuts and bolts

Adequate yield stress is essential if segregation is not to occur, allowing the formation of a homogeneous deposit. The yield stress also determines the slope at which the material will come to rest, so an elevated yield stress is desirable when a steeper slope leads to more efficient storage (Sofrá and Bogner, 2001). Although the benefits are attractive, the yield stress of a slurry rises exponentially as water is removed and the solids content rises. Paste therefore, by definition, has an elevated yield stress compared to conventional slurries (see Table 1). It has been shown that paste cannot be produced when less than 15% by mass passes the 20 micron size (Cincilla et al., 1997).

Several equipment manufacturers have invested in research and development of high rate or deep bed thickeners designed to extract more water and produce a thicker underflow. To overcome the elevated yield stresses associated with paste, the floor of the thickener must be steeper and the thickener deeper so more head is available to mobilise the underflow. All else being equal, the retention time in the thickener must be greater when less volume exits as underflow, requiring a larger vessel with more time required to draw off a more concentrated underflow. This is overcome to varying degrees through the use of flocculants that aid settling, so the overflow is clear.

Various innovations have been implemented in deep thickeners to aid settling while keeping the settling material moving towards the discharge point. Clearly, more effort is required to move a heavier bed of settled material and the torque on the rake is eventually a limiting factor (Arbuthnot and Triglavcanin, 2005).

When sizing pumps and pipes for slurry transport, research has demonstrated that the system is most efficient when operated at the laminar–turbulent transition. When solids concentrations are increased above that, head losses increase dramatically. Paste is by definition at a solids content far beyond that, with behaviour better described as a Bingham fluid, and centrifugal pumps are no longer appropriate. Positive displacement pumps are required to overcome the yield stresses.

Options for transport are limited due to the slump of the paste — it is not a solid and may be thixotropic, displaying a lower yield stress once sheared. Transport in a truck or conveyor belt may therefore be inefficient or messy, leaving pumping as the best alternative. As mentioned before, pumping materials of this consistency is not efficient, so when the disposal site is some distance away from the mill it may be beneficial to pump slurry with lower solids content and have the water removal operations close to the disposal site.

5.3 The reality

The potential for water recovery and limitation of longer term environmental impacts remains attractive, but paste technology is still largely reserved for underground backfill operations. Factors that have perhaps limited its application in surface disposal include the cost of equipment and the need to maintain a stable operation (highly sensitive to moisture content of tailings materials exiting the mill and fines content). When the ore is variable, particularly with respect to fines content, it is difficult to maintain a reliable throughput at the thickener. Most operators prefer to optimise the milling and metal recovery operation, sacrificing performance of the tailings disposal system.

Although the removal of a considerable portion of the water results in a homogeneous and fairly dense tailings deposit, it remains to be demonstrated that the liquefaction potential is eliminated. In most cases a reclaim pond is still required to capture runoff. In reality then it is difficult to realise the potential benefits of a smaller containment dyke and reclaim pond: those elements are still required and, in regions with high seismic risk, need to be constructed to the same level of care.

The absence of fines in, for example, porphyry copper tailing, tends to make paste impractical in these operations. The issue of scale has also been a challenge as the torque required to move the rakes in a deep bed thickener limits the diameter of the units.

5.4 Application

The most common application for paste technology is applied for backfill operations where cement is added to improve strength gain. For surface disposal situations, it has been shown for example that the addition of cement as a binder can reduce the leachate concentration of metals. For the addition of cement to be effective, the water:cement ratio must be limited through removal of a large portion of the water in the tailing. In special situations then, where metals mobility must be limited, paste technology may be warranted. The application is limited by complexity of the operation, inefficiency of materials handling, and the associated difficulty of maintaining a consistent operation. It might best be applied close to the point of discharge, where adequate elevation difference is available to aid disposal, and the containment is easily provided with a large margin for error. When an open pit mine is available for backfill, but metals mobility is a concern, application of paste technology may be a viable alternative to conventional disposal techniques.

6 Thickened tailings disposal

6.1 The promise

The driver for implementing a thickened tailings disposal is generally related to one or several of the following topics:

- Water savings: recovering the water in a thickener is more efficient than sending the water to an impoundment where evaporation, infiltration and the water trapped within the tailings voids will reduce the amount of reclaimable water with respect to the thickener. This is an important feature for areas where fresh water is limited or its cost is high.
- Reduced requirements for containment structures: thickened tailings material has the potential for obtaining higher beach slopes and higher shear and cyclic strength than conventional tailing. Therefore, where a suitable area for tailings deposition is available, this could result in smaller embankments and thus reduce the capital expenditures related to the tailings storage facility.
- Reduced environmental impacts: having less water in the tailings materials and lower containment structures both equate to favourable attributes that may be more likely to be permitted expeditiously. Because more water is recovered from the thickener, the lower fresh water make-up requirements are an additional positive environmental feature for the project. Drawing less water will likely improve public perception towards the project.

Despite the drivers, the common denominator for implementing thickened tailings is to reduce overall cost of tailings storage.

6.2 The nuts and bolts

In order to achieve thickened tailings materials within the 50 to 70% solids range, a mine operator must rely on the following:

- Thickeners: the 50 to 70% solids range can be obtained using conventional, high-rate or high-density thickeners. For conventional or high rate thickeners output usual is on the order of 50–55%; for typical copper tailings and for high density thickeners, this number can increase to 65%. The underflow density will depend greatly on the physical and chemical characteristics of the tailings material and of the flocculant used. Normally, coarser tailings materials tend to settle faster and obtain higher solids content from the same thickener than finer tailings materials. Clay content is also an important factor affecting the underflow density.
- Flocculant preparation plant: in order to improve sedimentation velocity and efficiency, flocculants may be added to the tailing. For copper tailing, a typical dosage is on the order of 15 to 30 grams per tonne of tailing. This facility includes tanks for mixing fresh water with the flocculant and holding the solution for a period of time before injecting it to the thickener or the tailings line upstream of the thickeners.

- Shear thinning: depending on the solids content and the physical and chemical characteristics of the tailing, the underflow of the thickener may have a high yield stress that could hinder transport to the deposit. When the slurry is thixotropic, shear thinning pumps are installed close to the thickener underflow with the sole purpose of reducing the yield stress of the pulp to facilitate the transport. This centrifugal pumping system is designed to produce strong agitation of the pulp but not to generate pressure for transporting the tailing.
- Pumps: depending on the yield stress of the agitated slurry, pumping should be done using centrifugal or positive displacement pumps. Normally, for yield stresses of more than 100 Pa, positive displacements pumps are required. The cost of positive displacement pumps is significantly higher than centrifugal pumps for the same flow.
- Pumping line and discharge points: depending on the working pressures, and the physical and chemical properties of the tailing, the transport lines can typically be built from steel or HDPE. Coating might be necessary in steel pipes to reduce wear and tear from the material. In order to reduce the velocity at the point of discharge and facilitate the development of steeper beach slopes, a number of discharge points are necessary. Generally, a maximum flow of 3,000 tonnes per day per discharge point is the rule of thumb for maximising beach slopes for a given tailing. Head loss due to the number of discharge points should be considered in the pumping design.

6.3 The reality

The first thickened tailings facility was implemented in 1973 at Kidd Creek, a copper–zinc mine in Canada, under the guidance of Professor Eli Robinsky. Since then, several examples of thickened tailings deposits have been implemented in Western Australia. Western Australia has a favourable combination of high evaporation, low precipitation and expansive, flat surfaces that facilitate the operation of a central discharge thickened tailings deposits. In addition, the low seismicity of the area reduces the risk of slope instability.

Application of thickened tailings technology is currently limited to low to moderate production rate facilities. Nevertheless, an increasing number of projects in early stages of engineering are considering thickened tailings disposal methods. A list of some operating facilities is provided in Table 4.

Table 4 Summary of thickened and paste tailings projects implemented worldwide (Williams et al., 2008)

Mine Site	Location	Ore Type	Start Year	Status	Typical Rate Mtpa	Thickener Details: Type	No.	Dia. m	Unit Load $t/m_2.hr$	Floc. Rate g/t	Tailings Slurry Properties: SG	Conc % w/w	Disposal Scheme	Beach Slope Achieved: Max %	Range or Typical %	Reference
Surface Disposal:																
Kidd Creek	Ontario, Canada	Copper / Zinc	1973	Active	2.92	HC	1	35	0.37	20 to 25		63	CTD	2.5	1.5	Lord, 2003
Elura	NSW, Australia	Zinc	1981	Active	1.0							60	CTD Segmented	1.7		Williams & Seddon 1999
Argyle	WA, Australia	Diamond	1985	Deactivated	3.3-6.5							72 (??)	CTD Segmented	10 target		McMahon et al., 1996
Peak[1]	NSW, Australia	Gold	1992	Active	0.4	HR	1	8	0.97	10 to 15		55-62	CTD	2.5 +	1.5-2.0	Williams & Seddon, 1999, ATC Internal
Union Reefs	NT, Australia	Gold	1995	Closed 2001	2.0-3.0	HR	1					<55	DVD	0.9		Williams & Seddon, 2003
McArthur River	NT, Australia	Lead	1995	Active	2.4							60	CTD	1.0		Williams & Seddon, 1999
Cluff Lake	Saskatchewan, Canada	Uranium	1995	Closed 2002	0.32	HD	1	26	0.02		2.7	52	DVD	3.0		Lord, 2003
Ernest Henry	Qld, Australia	Copper	1997	Active	7.0	HC	1	70	0.22		3.3	75	CTD	1.1		Williams & Seddon, 1999
Mount Keith	WA, Australia	Nickel	1997	Active	10.5							44	CTD Multiple	2.0		Williams & Seddon, 1999
	WA, Australia	Nickel	1997	Active	10.5							44	CTD Multiple	1.0		Bentel, Discussion Paste 2007
Blendevale (Pilara)	WA, Australia	Lead	1998	Closed	1.5							65	CTD	1.5		Williams & Seddon, 1999
Warkworth #2 Redbank	NSW, Australia	Ash	1998	Active	0.1							70	Side Hill	5.0		ATC Internal
Ekati	Canada	Diamond	1998	Active	1.6	HR DC	2	12	0.86		2.7	40	Surface	1.0	1	Lord, 2003
Strathcona	Canada	Nickel	1998	Active	0.5	HR DC	1	10	0.23	20	2.9	45		1.5	1.25 - 1.5	Paste, 2006
Century	Qld, Australia	Zinc	1999	Active	4.3	HR	1	45	0.33	32-38	2.8	52-58	DVD	1.0	0.6-1.0	Murphy, 2006
Sunrise Dam	WA, Australia	Gold	2000	Active	3.6	HR	1	24	0.97	19		64	CTD	2.0	1.0-2.0	Williams & Seddon, 2004
Bulyanhulu	Tanzania	Gold	2000	Active	0.7	O								10 max		Landriault, 2000
Myra Falls	Canada	Copper / Zinc	2003	Active		P	1	25				65-68		3.0		Lord, 2003
Kimberley CTP[2]	S. Africa	Diamond	2003	Active	8.6	P	5	15	0.36	<50		44-57	CTD	1.5	1	Houman & Johnson, 2003
Osborne	Qld, Australia	Copper / Gold	2004	Active	1.34	HR	1	9	0.77		3.6	72-76	CTD	4.0	3	McPhail et al., 2004, Brent and Dobb, 2006

Thickeners	
HR	High Rate
HR DC	High Rate Deep Cone
HD	High Density
HC	High Compression
P	Paste
O	Other, refer notes

Disposal Schemes	
CTD	Central Thickened Discharge
DVD	Down Valley Discharge

Notes:	
1	Max slope increased to 5% after switch to multi-spigot discharge
2	This is now planned to be a continuing surface disposal facility

Table 4 (cont.) Summary of thickened and paste tailings projects implemented worldwide (Williams et al., 2008)

Mine Site	Location	Ore Type	Start Year	Status	Typical Rate	Thickener Details				Floc. Rate	Tailings Slurry Properties		Disposal Scheme	Beach Slope Achieved		Reference
						Type	No.	Dia.	Unit Load		SG	Conc		Max	Range or Typical	
					Mtpa			m	$t/m_2.hr$	g/t		% w/w		%	%	
Surface Disposal (continued):																
Cobriza	Peru	Copper	2004	Active	1.8	P	1	14	0.43	35	3.73	77	DVD/side hill			V. Gonzales (D.O.E.) Paste 2005 , p261+
Miduk	Iran	Copper	2005	Active	4.8	P	4	16	0.73	25 to 30		63	DVD	2.5		ATC Internal
Ellendale E4 (TSF 2A)	WA, Australia	Diamond	2006	Active	3.7	HR	1	34	0.50	80	2.8	47-49	DVD			ATC Internal
Douglas	Vic, Australia	Mineral Sands	2006	Active	2.0	HR	1				2.7		CTD			ATC Internal
Lone Mountain	USA (East)	Coal	1997	Closed 2007	0.8	Belt Press[3]	4	na	na	55	1.9	55	Trucked, Side hill	2.0	1	Gupta & Johnson, Paste 2007
	USA (East)	Coal	2007		0.8	P[4]	1	15	0.55	55	1.9	55	DVD	2.0	1	Gupta & Johnson, Paste 2007
In-Dump Disposal Schemes:																
La Quinua[5]	Peru	Gold	2008	Active (?)	5.0	HR	1	32	0.76	11	2.8	69	DVD			Kerr et al., Paste 2007
In-Pit Disposal Schemes:																
EKAPA	S. Africa	Diamond	2002	Active	0.8	P	1	15	0.17	80-100	2.65	53-57	In pit			Hohne et al., 2004
Pajingo	Australia	Gold	2002	Active	0.73	P	1	14	0.17			59-61	In pit			Gregory, 2003
Hazelwood	Australia	Lignite Ash	2006	Active	0.2	HR	1	22	0.02	80-100	3	40-45	In pit	low	<1%	New Kearn & Sweeney, Paste 2007
Granites	Australia	Gold	1999	Closed[6]	0.02	HR	1				2.75	55-60	In pit	2	n/a	ATC Internal
Red Mud:																
Gove	NT, Australia	Bauxite	1972	Active									CTD			No details published
Vaudreuil (Jonquiere)	Canada	Bauxite	1987	Active	0.45	P	1	12	0.49		-3.0	45		4.0	3.0-4.0	Lord, 2003
Alcoa Kwinana	WA, Australia	Bauxite	1989	Active	1.9	HC	1	50	0.12	60	-3.1	50	Dry Stacking	1.2	1.0-1.2	Cooling, 2000
Alcoa Pinjarra	WA, Australia	Bauxite	1987	Active	3.3	HC	1	90	0.06	50-80	-3.1	50	Dry Stacking	1.2	1.0-1.2	Cooling, 2000
Alcoa Wagerup	WA, Australia	Bauxite	1991	Active	2.2	HC	1	70	0.07	60	-3.1	50	Dry Stacking	1.2	1.0-1.2	Cooling, 2000
Aughinish	Ireland	Bauxite	1993	Active	1.7	O						63	CTD	2.7	1.5-2.7	Phil Newman, Paste 2006

Thickeners	
HR	High Rate
HR DC	High Rate Deep Cone
HC	High Compression
P	Paste
O	Other, refer notes

Disposal Schemes	
CTD	Central Thickened Discharge
DVD	Down Valley Discharge

Notes:	
3	Belt pressed to be decommissioned following commissioning of paste thickener
4	Westech Deep Bed paste thickener at TSF site
5	Knight Piésold/Paterson and Cooke
6	Thickened tailings used to cap in-pit deposit

To our knowledge, there currently are no known full scale thickened tailings disposal applications in South America for large-production mines (copper, gold). The Esperanza project, located in northern Chile in the Atacama Desert at an altitude of 2,300 m above sea level with a design production rate of ~95,000 tpd, will be operational at the end of 2010, and will be the largest thickened tailings facility in the region and possibly in the world. Some of the region-specific issues for implementing this type of technology can be summarised as follows:

- Mining at high-altitude sites in the Andes Mountains, with steep valleys available for tailings storage, reduces the convenience of thickened tailings facilities where the anticipated beach slope is flatter than the valley slope (requires containment dam similar to a conventional tailings facility).
- Large areas for disposal are required to maximise evaporation from the tailings beach, this in turn, is needed to improve the density and strength of the tailings material.
- Large production mines require large ‘prototype’ equipment for thickening and transport. Generally, such equipment has not yet been proven elsewhere. Alternatively several units of smaller equipment can be used; this adds to the project cost.
- Concerns regarding the seismic behaviour of the thickened tailing, where, in order to take advantage of beach slope, the top of the tailings beach can be higher than the crest of the confining dam, and thus having the potential for overtopping in case of a liquefaction failure. In such a case a large containment dike is required as for conventional disposal so the potential capital cost saving cannot be realised.

6.4 Application

The capital cost of specific equipment, such as high rate thickeners, pumps and lines and the operational costs, including high dosages of flocculants, high energy consumption and specialised operators usually make thickened tailings alternatives more expensive than conventional disposal. The main economical benefit of using thickened tailings is associated to with a smaller embankment. This advantage can only be achieved in flat topographies, where deposition angle is steeper than the valley slope. When savings in embankment costs can be realised, thickened tailings disposal is a very attractive option.

As a result, thickened tailings disposal is recommended for use at mines with small to moderate production rates that do not require prototype equipment or many units of equivalent smaller equipment, and where disposal areas are spacious and almost flat, or where the difference in elevation between the mill and the point of discharge is advantageous. This method can also be suitable for areas with weak foundation materials, which preclude the development of an embankment. The advantages of thickened disposal may not be realised in areas with heavy precipitation, low temperatures and little sun to enhance evaporation.

7 Conventional tailings disposal

7.1 The promise

Conventional tailings disposal is widely used and, at most mines, remains one of the least expensive methods of disposal. It uses dams and embankments to form an impoundment where the tailings can settle from suspension into a stable consolidated deposit. Selection of the embankment type must be based on the specific characteristics of each mine, mill, tailings grind, climate, seismicity topography and other factors.

The driver for implementing a conventional tailings facility is generally related to one or several of the following topics:

- Efficiency and stability of operation: because of its long history, conventional tailings disposal has proven to be an effective method for disposal of tailings material. Additionally, the method’s pervasive use and long history has provided information for successful operations.
- Efficiency and cost: as a result of its long history, much is known about conventional tailings disposal; best practices have been established which makes for efficient operations. In addition, in

many instances, conventional tailings disposal is less expensive than the ATD methods previously discussed.

- High production rates: conventional tailings deposition remains the only proven technology at mines with high production rates.

The practice referred to here as 'conventional' has been developed through many years of experimentation and offers to be the most efficient with respect to energy consumption and reliable with respect to operational stability. The slurry density where dynamic head is lowest is generally targeted, with measures incorporated to recover the excess water from the storage facility.

7.2 The nuts and bolts

Tailings materials are generally discharged from the mill as slurry between 25 and 45% solids by weight. The conventional method utilises shallow thickeners that increase the tailings solids content to concentrations that optimise hydraulic transport of solids. The thickeners are usually located next to the concentrator and along with them is a flocculation plant. Depending on the characteristics of the tailing, different dosages of flocculants are used to improve efficiency of thickening and clarity of reclaimed water. Thickeners increase tailings slurry densities up to 30 to 55% solids by weight. The recovery water is collected for reuse in the mill.

The hydraulic transport system of the thickener underflow is aided by gravity or centrifugal pumps as required by the topographic conditions, or a combination of both systems. In the gravitational transport, reinforced concrete launders and steel or HDPE pipes are commonly used. For pressurised flows, steel pipes are typically used. Discharges into the impoundment are relatively simple and usually do not require special facilities.

The impoundment site for storing the tailings is chosen to make optimal use of natural topography and geologic conditions in order to minimise embankment volume. The embankment can be constructed with mine materials, borrow area materials or, in some cases, coarse-grained tailing.

Where embankments are being built with the coarse fraction of the tailing, the tailings are separated with hydrocyclones. The coarse fraction (sand) is transported hydraulically to the embankment where it is discharged by spigots. The fine fraction is hydraulically transported to the impoundment. The low fines content in the sand is essential to efficient and fast drainage and to ensure that piezometric levels that may constitute unstable conditions are not formed in the body of the dam. The amount of sand available in the tailings material, as well as the size and growth requirements of the dam, dictate the method of construction.

Where the tailings material is not suited to a sand dam, a compacted earth material may be chosen, using borrow material or mine waste rock, or a combination of both. The selection of dam construction type is driven primarily by geologic, hydrologic and economic factors.

Conventional slurried tailings deposition should have sufficient impoundment surface area to allow segregation of tailings by particle size as well as separation of process water from the tailings solids. Under these conditions, the settled tailings solids create a beach with a surface developed at slopes of 0.5 to 2%. The process water separated from the tailings is collected in a supernatant pond for additional solids settlement and eventual recirculation to the mill.

As a result of the low density with which the tailings materials are deposited, large storage facilities can be vulnerable to liquefaction. Tailings facilities are therefore designed to ensure safety and containment of the tailings under extreme loading conditions.

In arid climates, conventional tailings storage facilities offer favourable conditions for final closure, where evaporation aids drying of the tailings materials and improves stability. Usually, the surface of the TSF is covered or protected to prevent wind and water erosion. Final closure often extends over many years and requires monitoring to ensure physical and chemical stability over the long term.

7.3 The reality

Around the world conventional tailings disposal remains the most widely used method of tailings disposal, especially for mines with high production rates. In addition, conventional tailings disposal is uncomplicated with a long history of best practices. Conventional tailings disposal is usually less expensive than other alternative tailings disposal methods, particularly where the topography of the site precludes the requirement for large embankments. The favourable economics of the conventional method is due mainly to optimisation of the slurry density for lowest handling and transportation cost.

In areas where water supply is restricted, however, conventional tailings disposal may not make sense as the cost of water may make this disposal method prohibitively expensive. Large volumes of water are needed to transport and dispose the tailings and recover process water, and therefore it does not use water as efficiently as some other methods. Some methods of off-setting the inefficient use of water include maximising recovery of water from the tailings materials, controlling the size of decant pond to reduce evaporation losses, and managing discharge practices.

Conventional disposal requires natural topography and geologic conditions to minimise embankment size and maximise the tailings storage volume.

7.4 The application

Conventional tailings disposal is recommended for use at any production rate, but in particular at high production mines where the mine's topography lends itself to storage of the tailings in surface impoundments. Environmental concerns related to tailings storage can be minimised by favourable site geologic conditions and engineered controls or by lining the impoundment.

8 Summary and conclusions

Every mine is unique with respect to setting, material properties, water supply, mineral process employed, environmental obligations and energy cost. It is, therefore, difficult to prescribe a method of tailings disposal; each case must be evaluated on its own merits. In general however, optimisation of the slurry transport system remains sensible and will often lead to the employment of conventional disposal. It is encouraging that methods to recover more water for reuse in the process close to the mill are advancing rapidly, and where water is scarce, environmental risks high or the process warrants recovery of reagents or metal values in the water, removal of additional water can be achieved.

Early assessments of tailings properties with regards to sedimentation, rheology and geotechnics, as well as field conditions of the projected impoundment area, are key to evaluating the potential for implementing ATD methods. Using these basic data, comparisons of capital and operational expenditures between the different alternatives can be studied at prefeasibility or feasibility level engineering to assist early decision-making regarding tailings disposal.

To date it has proven difficult, except in specifically favourable circumstances, to achieve the potential environmental and cost benefits promised by thickened and paste tailings disposal. That is not to say that these methods should not be considered, only that the potential benefits may not be achievable in every case.

In many cases filtering can result in improved density and tailings storage efficiency, so when space is at a premium, filtering of tailings prior to disposal has potential. The operating costs are considerable, and transportation of solids is more costly than transportation of slurry, but some of these costs may be offset by the opportunity to reuse and therefore conserve water and space. In addition, the reduction of environmental risks makes it an attractive option as regulations become more stringent.

In summary, selections of the ATD technique has to be done on a case-by-case basis, taking into account the specific conditions and requirements at the mine.

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