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behaviour of high density tailings**

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Complete List of Authors:	Simms, Paul; Carleton University,
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1 **2013 Colloquium of the Canadian Geotechnical Society:**
2 **Geotechnical and Geoenvironmental behaviour of High**
3 **Density Tailings**

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5 P. Simms
6 Professor
7 Department of Civil and Environmental Engineering
8 Carleton University
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10 **Abstract**
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12 The breaching of containment of conventionally deposited mine tailings impoundments,
13 and the consequent release of tailings flows with long run-outs, unfortunately remains not
14 uncommon and often has devastating ecological and economic consequences,
15 occasionally including the loss of human life. Rather than the breaching of containment
16 itself, which can result from a number of causes (poor control of the phreatic surface,
17 unrecognized dam foundation issues), the contributing factor to the severe consequences
18 of dam breach is the low density and strength and / or susceptibility of the tailings to
19 liquefy or soften under loading, combined with the driving weight of the ponded water,
20 which allows for significant run-outs (in some cases 10's of kilometres) to occur. Hence
21 the motivation for alternative technologies that dewater tailings before deposition to the
22 point where reliance on containment is minimized or eliminated. In this paper, these
23 technologies are referred to as High Density tailings, which includes any technology that
24 at least produces non-segregating tailings that will form a sloped stack when deposited,
25 including thickened, paste, and filtered tailings. The paper explores a number of issues
26 related to high density tailings, including shear behaviour, dewatering behaviour, acid
27 generation, and surface deposition rheology. The paper concludes with some discussion
28 on what are the limitations on this technology holding back its wider adoption, and how
29 these limitations might be overcome.
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31 Keywords: tailings, thickened, paste, filtered, high density
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34 **Introduction**
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36 In many kinds of mining (base metal, precious metal, surface mining of oil sands,
37 bauxite), large amounts of water are used in mineral processing. Water lubricates the
38 grinding process in hard rock mining, and facilitates other extraction or separation
39 processes used in other types of mining, such as flotation (Willis 2006). Transport of the
40 ore slurry from unit to unit within the mill or plant is also facilitated by high water
41 content. Consequently, tailings conventionally exit the mill at very high water contents
42 (Often at ~100 % gravimetric water content for hard rock mining, ~200% for oil sands
43 and bauxite mining), very much above the liquid limit of these materials (Vick 1990).
44 The volume of water deposited with the tailings is substantial: in a hard rock mine
45 operating at 100,000 tonnes per day, 100% water content implies 100,000 m³ of water

will be deposited with the tailings, an amount greater than the domestic use of a city of 1 million in North America. Natural dewatering of tailings in impoundments is slow due to the small particle size (predominantly silt sized, often with a substantial clay size fraction). Water recovery from tailings is indeed a major economic driver for dewatering the tailings prior to deposition, especially in arid climates where the cost of water is high.

Another motivation for dewatering tailings before deposition is to eliminate or limit the consequences of dam failure that have plagued conventional slurry deposition. The most recent example is the failure in the Bento Rodriguez district of Brazil in October of 2015, which killed 17 people. A recent example in Canada is the widely known Mount Polley failure in 2014. Failures and the occasionally devastating consequences of conventionally deposited tailings from base and precious metal mines are documented in a number of sources, including the ICOLD report (International Commission of on Large Dams) in 2001, and summarized in various documents and websites (e.g. www.tailings.info). Individual cases documented in the research literature include the Merriespruit failure (Fourie et al. 2001; Fourie and Tshabalala 2005), various failures in Chile attributed to seismic events (Dobry and Alvarez 1967; Villavencio et al. 2014), the 1978 Isu-Ohshima earthquake (Marcuson et al. 1979), and the 1985 Chilean earthquake (Castro and Troncoso 1988). Failures are more common for upstream tailings structures, where the tailings themselves serve as the foundation of the dam (Berti et al. 1988; Chandler and Tosatti 1995; Martin and Roberts 2002). However, whether upstream or not, the susceptibility of tailings to rapid strength loss is what results in long run-outs and consequent large impacts following a dam breach (Davies et al. 2002). This has been postulated to be due to collapse behaviour under undrained loading that is known to occur in loose sands (Sladen et al. 1985), and in silty sands (Yamamoto and Lade 1997 and Hyde et al. 2007), the consequence for tailings being that collapse behaviour can manifest in either the segregated sand fraction or in the whole tailings. In any event, it is clear that tailings deposited as a slurry are susceptible to substantial loss of strength, whether by cyclic loading, or by a change in static load induced by a rise in the phreatic surface or dam breaching. Such failures have often resulted in very long run-outs with devastating effects.

There is a spectrum of dewatering that may be employed before deposition. The degree of dewatering increases from thickened tailings, to paste, to filtered tailings. There is some variability in the usage of these terms (Jewell and Fourie 2012). In this paper, the following usage is adopted: "Thickened tailings" are dewatered sufficiently to eliminate grain-size segregation upon deposition, or in other words, to form a homogenous slurry. Homogenous slurries require dewatering to at least a volumetric solids content of 40% (Wilson et al. 2008), which is equivalent to about 65% solids content by mass (C_s) for hard rock tailings, depending on the specific gravity of the particles. Thickened tailings need to be transported as a turbulent flow in the pipeline, at a certain minimum velocity to avoid or minimize sedimentation in the pipeline. "Paste tailings" are further dewatered to the point where they may be pumped in the laminar range and do not have a terminal settling velocity, which usually requires a solids content in excess of 70% and a yield stress greater than 50 Pa. For paste transport to be possible, the tailings must have sufficient fines (the rule of thumb of 15% < than 20 microns - Engman et al. 2004). Various equations exist for calculating the required transport velocity for thickened

tailings (e.g. Oroskar and Turian 1980) and for calculating the laminar – turbulent regime boundary. Transport of high density tailings is addressed in a range of sources (e.g. Paterson 2011), and is beyond the scope of this paper. Tailings may be further dewatered by mechanical or vacuum filtration to produce a filter cake, usually producing a solids content greater than 77% (Weatherwax and Kipara 2010; Lara et al. 2013), which is no longer practically pumpable, and is usually conveyed to the tailings disposal site by belt conveyors or trucks. Table 1 summarizes the definition, the relative water recovery, and range of the yield stress expected from each dewatering technology commonly seen for hard rock tailings. Bauxite and oil sands tailings, for example, typically have higher water contents at a given yield stress due to the higher clay content of those tailings (Sobkowicz 2013).

The economic feasibility for new sites considering high density tailings depends on dewatering and increased transport costs being offset by the cost of water and dam construction cost savings. High density tailings can be financially justifiable on this basis depending on site characteristics, such as water availability, size of the mining operation, and local topography (Fitton and Roshidieh 2013). When thickened tailings technology was first pioneered at the Kidd mine in Ontario by Eli Robinsky (Robinsky 1975), the driver was poor soil conditions for large dam construction. Several operations have switched between conventional deposition to high density tailings deposition, in order to maximize use of the existing tailings impoundments footprint (Nueves Corvo in Portugal - Lopez et al. 2015), Musselwhite Mine in Northern Ontario - Kam et al. 2011). Reducing water consumption by the mine is not only desirable in climates where water availability is low, but in many jurisdictions, limiting the volume of tailings and minimizing the amount of volume of “mining-exposed” water is desirable from an environmental perspective for many stakeholders in mining impacted regions (Jacobs 2014).

Where site conditions are favourable, this method will clearly be adopted in future due to the aforementioned financial and social drivers. Nevertheless, there are a number of drawbacks or uncertainties that hold back wider adoption of this technology. Table 2 describes a number of differences between conventional and high density tailings and the consequences for geotechnical or geo-environmental performance of the facility.

The two most important uncertainties are 1) how the geometry and overall slope of tailings stack will develop, and 2) what are the strength characteristics of a high density tailings deposit. The first uncertainty is probably the most bedeviling obstacle to wider adoption of high density tailings technology, as the overall slope of the impoundment governs many important costs that must be assessed early on in the preliminary design of tailings structures. The slope not only affects the capacity of a given footprint and dam volume, but also affects water management costs (runoff of the tailings surface) and reclamation costs. How the tailings distribute in the impoundment also influences the relative exposure of the tailings to drying (Shuttleworth et al. 2005; Cooper and Smith 2011).

The paper will discuss aspects of the dewatering behaviour, strength, and deposition rheology (stack geometry) of high density tailings, and conclude with some discussion on how wider adoption of this technology can be facilitated.

Geometry, deposition process, and beachslope prediction for thickened and paste tailings

Deposition of high density tailings that are transported in a pipeline can be done in several ways, including single point discharge (also called central thickened discharge), single point discharge where the direction of the discharge is periodically changed, multiple point discharge within an impoundment, and multiple point discharge on an embankment. Discharge can be split or cycled between the discharge points. All of these methods generate gently sloped deposits that range in average slope between 0.5 and 4 %, with most sites exhibiting a slope less than 3%. Table 3 gives examples of sites employing some of the measures mentioned above and their average beachslope angles. Deposition has been ongoing for at least two years at all the reported sites. The reported average slopes are taken from the referenced sources. Yield stress values are obtained from rheograms or from slump tests.

Generally, there are two factors that are believed to limit the over-all impoundment's slope (Williams et al 2008; Simms et al. 2011):

1. The self-eroding nature of the tailings, which form channels during the deposition process
2. The shear strength of the tailings

Tailings deposited from the end of the pipe will initially exhibit a relatively thin, contiguous flow that spreads out from the deposition point (sheet flow) forming a roughly symmetric deposit. At this point the overall profile is characterized by a slope that changes from steep at the toe, to relatively flat near the deposition point (Williams et al. 2008; Simms et al. 2011).

But at some point, the momentum of tailings coming out of the pipe is no longer dissipated into the spreading deposit, but instead the tailings self-form a channel within the immediately previously deposited tailings. This channel then travels some distance down the impoundment, until the flow again converts to sheet flow. Eventually, tailings begin to back up the channel, flowing out the sides of the channel onto the previously deposited tailings. Thereafter, a new channel forms, and the process repeats. After or close to the initiation of channel flow, the deposit geometry tends to exhibit an increasing slope towards the deposition point. This shape, where the slope increases towards the deposition point, is characteristic of all mature thickened tailings and paste surface deposits (Williams et al. 2008; Simms et al. 2011).

The geometry that develops during sheet flow (early deposits in the field, as well as bench scale flow tests) is well-described using lubrication based approximations of non-Newtonian flow (Henriquez and Simms 2009; Mizani et al. 2013). An important result of this theory is that the average slope of the deposit formed by sheet flow is inversely correlated with the scale of the flume test: this implies the angle measured in a flume test

has no direct relevance to the angle achievable in the field, as this angle is a function of the size of the flume test. Practitioners must take this in mind when extrapolating probable field beachslopes from laboratory flume tests: direct application of beachslopes measured in laboratory flumes should not be used (Simms 2007; Gawu and Fourie 2010).

The deposition process can therefore include both forward deposition conveyed by channel flow, and backward deposition due to backing up of the channel towards the deposition point and overflowing of the channel. Similar behaviour is reported in both the field and in laboratory physical models of alluvial deposition (van Dijk et al. 2009; Hamilton et al. 2013), where the slope varies from a maximum during episodes of sheet flow and aggradation, and a minimum during episodes during channel erosion. Figures 1 through 3 give some examples typical of high density tailings geometry.

The two most commonly used methods to predict the beachslope assume that the slope is limited by the erosion-deposition equilibrium that happens within the channels themselves: these methods were initially developed in the theses of Tim Fitton (2007) and Gordon McPhail (1994). Both methods predict that beachslope is inversely related to flow rate, and increases with the yield stress of the fresh tailings. The chief difference is that Fitton's method predicts a single value of beachslope, whereas the method of McPhail predicts a non-uniform beachslope, that changes in slope (decreases) with the size of the impoundment. Fitton and collaborators have since modified their method to incorporate variable output from a thickener (differences in density) to explain the variable profile of real deposits. Simms et al. (2011) re-presented and compared both these methods, as implemented as of late 2010, and compared the predictions of each method with one real case of high density tailings deposition.

Various lines of evidence suggest, however, that the overall slope may also be constrained by the strength of the material. There are many observations of local slope failures (Crowder 2003; Shuttleworth et al. 2005; Wates et al. 2015) during deposition. Slope stability failures have been reported during deposition at the Nuevas Corvo mine in Portugal (Lopez et al. 2015). Deposition angles have often been improved by alternating the location of the deposition point – Cooper et al. (2011) reported a case in South Africa where an increase in overall beach angle from 0.5% to 2% was induced by cycling the tailings and allowing tailings to desiccate before subsequent burial.

A simple slope stability analysis also supports the importance of strength to beachslope. Simms et al. (2013), performed slope stability analyses of 2 D idealized thickened tailings deposits with uniform slopes, generating the results shown in Figure 4. These authors made the assumption of uniform shear strength conforming to density at the cessation of sedimentation or self-weight consolidation in a thin layer (< 1 m), ignoring any gain in density with depth, either occurring due to consolidation or desiccation. The authors used Geoslope, however, these results can be easily reproduced using any slope stability method or software. Figure 4 shows that the stable slope decreases as a function of impoundment size, but tends towards a finite value. For a shear strength of 0.5 kPa, corresponding to the post-sedimentation shear strength of at least two non-segregating

gold tailings measured by slump tests and using a vane (Simms et al. 2007; Daliri et al 2014), a stable slope of about 3% to 6% is predicted. Also important to note for the validity of this exercise, the predicted failure surfaces are quite shallow.

Research is ongoing using various CFD techniques to approach the beachslope problem from a more fundamental perspective. Mizani and Simms (2014) discusses the role of shearing and aging on surface deposit geometry. Baboaglu and Simms (2015) investigated modelling of thickened tailings deposits using the smooth particle hydrodynamics method. Gao and Fourie (2014) and Mizani and Simms (2014) have investigated modelling of thickened tailings flows using finite volume techniques.

Dewatering behaviour

Sedimentation / self-weight consolidation in a thin lift

Thickened and even paste tailings deposited in will exhibit some degree of sedimentation or self-weight consolidation within hours to days after deposition, even when deposited in quite thin lifts (Daliri et al. 2015; Fisseha et al. 2010; Simms et al. 2007). For hard rock tailings, the initial sedimentation or self-weight consolidation can occur within two or three days (Dunmola 2012; Simms et al. 2007). Furthermore, the final density after initial self-weight consolidation in the lift appears to be relatively independent of the solids content at deposition, as long as a non-segregating tailings is produced. Figure 5 shows settling tests on a gold tailings prepared at a range of initial solids content (Manlagnit 2011) and for lift thicknesses up to 0.50 m.. There is a small (~ 0.05) difference in final void ratio. If this behaviour is general, it is quite significant, as it would imply that geotechnical benefits of thickening may be realized for lower solids contents than previously thought.

Evaporation

High density tailings will naturally undergo some degree of desiccation in most climates, which can be maximized by spreading the tailings in relatively thin layers using alternating point discharge. The rate of evaporation (Actual Evaporation, AE) is a function of the potential evaporation (PE) rate. PE is a function of climatic parameters, whereas AE depends on the hydro-geotechnical characteristics of the tailings such as compressibility, hydraulic conductivity, and the soil-water characteristic curve. Bussiere (2007) gives a comprehensive review of hydro-geotechnical characteristics of tailings. The theory of soil evaporation is reviewed in a number of sources, including Wilson et al. (1997) and Bitelli et al. (2008). Classically, evaporation starts at the PE rate, subsequently decreasing due to an increase in total suction at the soil surface (Wilson et al. 1997). Salinity and cracking are also important factors. The influence of salinity and cracking on evaporation from conventional tailings have been studied by several authors, including Fujiyasu et al. (2000, 2001).

For hard rock thickened tailings of low plasticity, the evaporation rate follows classic soil drying (Simms et al. 2007; Fisseha et al. 2010; Daliri et al. 2016), where evaporation decreases with time after deposition of fresh tailings. This decline may be accelerated by high salinity (or high concentrations of dissolved mass in the pore-water), as salinity decreases evaporation by multiple mechanisms of osmotic suction, high albedo (reflectivity to shortwave radiation), and formation of a salt crust (Dunmola and Simms 2010; Dunmola 2012). While cracking does occur, the frequency and size of the cracks appear insufficient to substantially increase evaporation in low plasticity hard rock tailings (Simms et al. 2007; Fisseha et al. 2010; Daliri et al. 2016). In tailings with significant clay content however, cracking appears to be a very important mechanism to maintain relatively high evaporation rates. This has been recognized in field studies on conventionally deposited tailings (Fujiyasu et al. 2001) as well as mesoscale experiments of the type of Daliri et al. (2016), in which AE apparently increases past PE when cracks first appear, (Rozina et al. 2015), or serve to maintain relatively high AE values, despite crust formation on horizontal surfaces (Innocent-Bernard et al. 2014). Figure 6 and 7 show evaporation from mesoscale simulations ($\sim 1\text{ m}$ by 1 m in plan) of multilayer deposition, of a thickened gold tailings (solids content of 70%) and polymer flocculated mature fine tailings (MFT) (solids content of 35%), along with pictures of their different crack patterns. The gold tailings show no change in AE in response to cracking, which may be due to the relative thinness of the cracks, the notable salt formation initially within the cracks, and the relatively high hydraulic conductivity that allows for relatively uniform drying with depth. By contrast, there clearly is a strong correlation between increased AE and crack growth in the oil sands tailings. For all these studies, in which the tailings ranged from non-plastic to having a plasticity index of 40, PE ranged from 8 to 3.5 mm/day , and the salinity of the tailings ranged from 3550 to 1800 mS/cm , cumulative evaporation remained above $0.7 \times \text{PE}$.

Whether tailings are either purposely deposited in different layers by cycling deposition, or where disposal naturally switches between different areas of the stack during single point discharge, it is important to recognize that the drying time of individual layers is affected by the presence of underlying tailings. Initially, when layers that are de-saturated are overlain by fresh tailings, transfer of water from the fresh layers can be accelerated, and the initial self-weight consolidation of the fresh tailings is accelerated. However, after some time, if the fresh tailings then continue to dry, the flow of water will reverse, and then water will flow upwards from the older tailings. This has been shown by generic modelling by Simms et al. (2010), and subsequently experimentally verified by Dunmola (2012) and Daliri et al. (2016), and also evidenced by the change in direction of seepage gradients at some sites (Al and Blowes 1995). Generic modelling predictions from Simms et al. (2010), which simulate dewatering of a 0.5 m fresh layer sitting on top of deposit at least 20 m deep, with field data from the Buyanhulu and Musselwhite Mines is shown in Figure 8.

Drying is also necessary for filtered tailings to achieve optimum compaction water contents for compaction (Lara et al. 2013). Drying estimates in practice appear to be

based on local experience, or using the potential evaporation and assuming water loss from evaporation comes from the last deposited layer.

Influence of desiccation on subsequent consolidation

Buried tailings will also experience further consolidation, whether desiccated or not. For hard rock tailings, the effect of desiccation may increase their stiffness, such that they do not consolidate to the same void ratio at a given effective stress. This may confuse interpretation of field data, where the desiccated tailings may appear to be less dense, even though, as will be discussed later, they have higher strength. An example of different consolidation behaviour of gold tailings under k_0 loading with different stress histories is shown in Figure 9, where tailings are either desiccated, and subsequently consolidate, desiccated and then rewetted, and subsequently consolidated, or never desiccated before consolidation.

Generalized modelling of dewatering of high density tailings applied to thickened tailings

In practice, dewatering of thickened tailings is often modelled using large strain consolidation theory, which may or may not include some partial coupling or inclusion of desiccation. Numerical codes that have been used to estimate both desiccation and consolidation include the Mintaco model (Seneviratne et al. 1996), CONDES (Abu-Hejleh and Znidaric 1995), and a code developed by the software company SoilVision based on the coupling formulation of Vu (2002). The first two are large strain consolidation codes with some added capabilities to handle desiccation, but not unsaturated conditions. Both models terminate or ignore water contents below the shrinkage limit. This tends to result in underestimation of the contribution evaporation to dewatering. The SoilVision model requires 3D constitutive surfaces, which are quite difficult to determine experimentally. No model can handle stress history effects, in other words, none have memory, which is important for the case of multilayer deposition, where both volume change as well as wet/dry hysteresis may be important. Simms et al. (2010) and Fisseha et al. (2010) implemented a modelling methodology involving unsaturated flow to handle volume change hysteresis, that appears to work well for hard rock tailings but it does not consider large strain consolidation, and therefore is limited in its application to all tailings types. Qi et al. (2016) incorporated an unsaturated formulation based on Vu (2002) into a piecewise linear formulation of large strain consolidation that was partially verified using the results of Seneviratne et al. (1996).

Susceptibility to Acid Generation

While the absence of ponded water on top of the tailings has the benefit of lowering the hydraulic head for driving seepage out of the tailings, the tailings have greater exposure to oxygen at the surface than if they were submerged with a water cover. Oxidation in tailings is strongly influenced by the diffusivity of oxygen, which is in turn strongly

controlled by the degree of saturation (Bussière 2007). There is great variety of opinion among practitioners as to acid generation in high density tailings: some believe the lack of water cover exposes too great a risk to oxidation, whereas others believe that the improved hydro-geotechnical properties and other phenomena greatly reduce the risk of substantial acid generation.

It may be helpful to this issue to revisit the finding of several researchers who have studied the geochemistry of the Kidd Creek site, one of the original sites that used thickened tailings that was commissioned in 1973 (Robinsky 1975). Barbour et al. (1991) showed that the improved water retention properties of non-segregating tailings would tend to minimize the depth of oxidation compared to subaerially deposited slurry tailings. Al and Blowes (1995), who conducted a detailed geochemical and hydrogeological characterization of the site, however, showed that oxidation tended to proceed as expected for subaerial deposition, with the exception that the active zone of oxidation was comparatively shallow (~0.25 m at this site). These authors also noted that substantial oxidation only occurred in tailings that were exposed to the atmosphere at least for six months. Further, the desaturation that did occur could not be predicted based on hydrostatic conditions (that is, desaturation was deeper than the expected capillary fringe based on hydrostatic conditions), and was induced by transient drying. Lastly, the pathway for contaminant egress was predominantly from surface runoff or shallow lateral groundwater flow. The gradient at depth tended to switch between upward and downward flow, minimizing deep groundwater transport of contaminants. Limited data from other thickened tailings sites (Bulyanhulu - Bryan et al. 2009; Shuttleworth et al 2005; Neves Corvo- Lopez et al. 2015) suggests that the zone of oxidation is also relatively shallow (< 0.25 m), and acid generation can be mitigated by minimizing exposure time of fresh tailings. Deschamps et al. (2008) studied paste deposition using a 0.36 m thick column experiment, found that pH began to decrease only after 8 weeks after deposition. Martin et al. (2010) showed through modelling that evaporation promotes an upward gradient in thickened tailings stacks, which is in agreement with the field observations of Al and Blowes (1995) in this regard. Anecdotal reports of substantial oxidation at one site do exist, but this has been attributed to disturbance of the tailings by rehandling (Shuttleworth et al. 2005).

Planning disposal to minimize the acid generation may be aided by deterministic analysis of oxygen transport. Coupling of transport of gases such as oxygen to transient unsaturated flow models is well-established and incorporated into practice in related fields (e.g. cover design for both mine wastes and landfills), and has been done in the research domain for thickened tailings, ranging in simplicity from estimating oxidation based on 1 D diffusion of oxygen into drying thickened tailings (Bryan et al. 2009; Martin et al. 2010), to more sophisticated analysis incorporating reactive transport modeling (Ouangrawa et al. 2009). These analysis suggest that exposure time of fresh tailings is the key variable in minimizing substantial evaporation.

Shear Strength

Stability of high density tailings stacks have been calculated in practice typically using infinite linear slope stability calculations. The strength used in either based on post-liquefaction residual strength as determined by critical state parameters (Li et al. 2009 using the state parameter methodology of Been and Jeffries 1985), or by residual strength measurements by field vane or element tests (e.g. Reid and Fourie 2014; Reid and Boshoff 2015), or by CPT tests using the methodology of Olsen and Stark (2002). In some cases, the material-specific response to cyclic loading has been incorporated into design earthquake methods (Youd et al. 2001), where cyclic resistance ratio is either estimated using CPT measurements (as per Robertson and Wride (2001), used in the case of Seddon and Albee (2015)) or element tests. These methods require estimation of vertical effective stress and / or void ratio with depth, which may be measured, or estimated using large strain consolidation calculations: the latter has been done with or without consideration of desiccation. These approaches tend to predict relatively low stable beach slopes, especially when the residual strength is estimated from steady state concepts. For example, Poulos et al. (1985) analyzed the stability of an existing thickened tailings facility and found it be unstable for calculations based on residual strength. Poulos et al. (1985), however, stated that they expected the use of residual strength to be quite conservative, due to the large degree of strain required to reach this state in the tailings.

One of the factors not considered in the above analysis is the effects of desiccation on i) the density, ii) dissipation of pore-water pressure, which is underestimated by models with relatively simple or non-existent treatments of unsaturated flow, and iii) positive stress history effects on strength imparted by desiccation. The generation of matric suction may impart strength to tailings through the contribution of suction to effective stress and by stress history effects. The former has been studied by several authors, for example, Narveez et al. (2015), and Rassam and Williams (1999). The contribution of suction to strength requires that such suction not be dissipated in the tailing stack, for example, during heavy rains. The stress history effects imparted to subsequently saturated and consolidated specimens by desiccation, have been examined in the work of Al-Tarhouni et al. (2011), and Daliri et al. (2014, 2015, 2016), who imposed different stress histories with variable degrees of desiccation on gold tailings, using multiple methods of desiccation control, sample extraction protocols, and types of element tests (triaxial and simple shear). Other works on this topic include Cifuentes and Verdugo et al. (2009), who partially investigated the influence of desiccation using triaxial samples obtained from a drying box. Crowder (2003) performed triaxial tests on thickened gold tailings samples. Reid et al. (2012) has examined how the use of polymers in thickeners alters the strength characteristics of thickened tailings.

Daliri et al. (2014) imposed different stress histories (conceptualized in Figure 10) on samples of gold tailings, using various methods designed to simulate the deposition process: samples were prepared at water contents at likely high ends ($w \sim 38\%$, 70% solids) of density coming out of the thickener, and subsequently allowed to settle. As shown in Figure 5, these samples settle to water contents $\sim 30\%$, even for very thin lifts (low stress). Tailings were deposited in various containers (simple shear molds, or into

flumes, or buckets where the molds were either placed before tailings deposition or inserted later), allowed to dry, and subsequently re-saturated and consolidated under k_0 loading in the simple shear device. Samples were also generated by sampling (both buried molds and by driving thin-walled tubes) from multilayer mesoscale simulations of thickened tailings deposition (Daliri et al. 2016). Samples generated by these methods, showed similar vane shear – water content correlations to field vane measurements at two thickened gold tailings sites, as shown in Figure 11.

In simple shear, samples that did not experience desiccation exhibited contractive behaviour for a wide range of consolidation pressures (50 – 400 kPa). This suggests there is nothing inherent about the thickening process that eliminates the susceptibility of tailings to static liquefaction. If one takes stress paths of non-desiccated tailings from the simple shear tests reported in Al-Tarhouni et al. (2011), and Daliri et al. (2014), the collapse line (Sladen et al. 1985) has a fairly unique angle of 15-16 degrees.

However, once the tailings experience desiccation their behaviour changes substantially, displaying increasing shear hardening behaviour with increased degree of desiccation. This behaviour is preserved in samples subsequently consolidated up to 400 kPa (Daliri 2013; Daliri et al. 2016,). Similar trends exist in terms of cyclic loading (Al-Tarhouni et al. 2011; Daliri et al. 2014) and monotonic triaxial loading (Daliri 2013), whereby desiccation imparts a substantial increase in CRR (cyclic resistance ratio) or strength at a given void ratio. Notably, as shown in Figure 12, the monotonic behaviour changes to strain hardening at water contents substantially higher than the shrinkage limit (25% compared 18%) suggesting even a modest degree of drying changes the fabric – this is better than the previously held view by many practitioners that dilative behaviour occurs subsequently to desiccation to the shrinkage limit (ICOLD 2001). The influence on desiccation on fabric and its persistence under subsequently high loads can be detected by both mercury intrusion porosimetry and using image analysis of SEM pictures (Daliri 2013; Daliri et al. 2014). The influence of desiccation is also detected through the subsequent consolidation behaviour – desiccated samples tend to be stiffer, such that they exhibit stronger response at higher void ratios than samples that never experienced desiccation. It is also important that both the change in shear and volume behaviour is very different from the effects of overconsolidation. Over-consolidated tailings exhibit higher peak strengths but less strain hardening (even limited strain softening) post-peak than the desiccated samples (Daliri et al. 2014).

The observation that desiccation results in tailings that exhibit higher strength at lower densities than non-desiccated tailings must be kept in mind when field investigations of thickened tailings sites are undertaken – higher void ratios do not necessarily mean lower strength.

Discussion

Uncertainty with respect to beach slope is still an issue engineers have to contend with early on in design of high density tailings facilities. The growing database (for example Table 3) of documented field cases, however, and the examples of particular innovations (use of internal dykes to constrain flow and upstream construction on thickened tailings for example) to minimize the impact of this uncertainty will help. Fundamental research on beaching dynamics is only just beginning, in my opinion, and will yield helpful results in the future.

Documented field experience at several sites (in particular Kidd Creek and Neves Corvo) shows that risk of oxidation can be minimized by proper deposition control. It would be useful to establish whether the hydrogeological observation of Al and Blowes (1995) at Kidd Creek, stating that contaminant transport occurs largely through runoff and shallow subsurface flow, applies to other sites.

Given that containment and even upstream construction are now used with high density tailings, can these sites be appropriately managed to eliminate the risk of catastrophic failure under static loading? If one believes that the contributory phenomenon to large run-outs is the collapse behaviour of the material, then the answer would seem to be “yes”, if sufficient fraction of the deposited tailings would be desiccated. Zones of soft tailings would inevitably arise due to challenges with managing deposition, which might be potential failure surfaces. But even so, one may speculate that the whole flow slide would not liquefy, and the consequences of failure would be much less drastic. Nevertheless, it would be helpful if this could be proven, ideally through large-scale physical testing.

Conclusions

High density tailings sites have been successfully operating in a range of climates, from wet and cold (northern Canada) to very hot and dry (Chile, Australia) for many years. This paper has attempted to identify the key issues affecting performance of this technology, to provide guidance and perspective to practitioners, and to help focus further research. To summarize:

1. Operational experience and innovation are helping to mitigate uncertainty with respect to beachslope, however, substantial uncertainty remains as to the fundamental behaviour of beaching dynamics.
2. Acid generation has been successfully minimized or managed at a number of high density sites. Field and laboratory studies show that limiting exposure time of fresh tailings is the key to minimizing oxidation. It would be helpful to determine if the observations at Kidd Creek with respect to the nature of contaminant flow (shallow subsurface, and runoff) are general.

3. In a number of laboratory studies using different loading modes and scales, desiccation has been shown to increase the degree of strain hardening in high density tailings, whereas high density tailings with no desiccation are still susceptible to softening, at least in simple shear. How best to incorporate these results to minimize risk of long tailings runouts are left to practitioners. For researchers, the logical path forward is to verify this behaviour at larger scales, including simulation of failures at the largest scale possible.

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Figure Captions

Figure 1. Paste tailings disposal at a gold mine, showing layer sequencing early in deposition (Picture: courtesy of Jason Crowder)

Figure 2. Sheet flow at the termination of a self-forming channel (Photo: courtesy of Jason Crowder)

Figure 3. Self-forming channel at a gold mine (Photo: courtesy of Claire Samson)

Figure 4. Factor of safety for slope stability as a function of stack size as predicted from 2D slope stability analyses using an undrained shear strength of 0.5 kPa (modified from Daliri et al. 2012, with permission from ACG)

Figure 5. Sedimentation / Self-weight consolidation behaviour of a gold tailings thickened to different solids contents and deposited at two different thicknesses in laboratory columns (Adapted from Manlagnit 2011)

Figure 6. Evaporation (a) and cracking in mesoscale simulations of a multilayer deposition of high density gold tailings (b) (Adapted from Daliri et al. 2016)

Figure 7. Evaporation (a) and cracking (b) in a mesoscale simulation of multilayer deposition of polymer amended MFT (adapted from Rozina et al. 2015 with permission Australian Centre for Geomechanics)

Figure 8. Shallow water contents in drying thickened tailings compared to generic predictions of drying for a 0.5 m fresh layer – predictions from Simms et al. (2010), field data from Simms et al. (2007) and Kam et al. (2011).

Figure 9. Void ratio – effective stress relationship at end of consolidation under k_0 loading for thickened gold tailings with different histories of desiccation (adapted from Daliri 2013)

Figure 10. Possible stress paths for thickened tailings (modified from Daliri et al 2014, with permission from ASCE). Net normal stress is total vertical stress less the pore air pressure.

Figure 11. Comparison of vane shear tests on laboratory prepared specimens of gold tailings from the Bulyanhulu gold mine, with field data from Bulyanhulu and Musselwhite Mines (Musselwhite field data from Kam et al. 2011)

Figure 12. Effect of desiccation history on subsequent shear behaviour of resaturated tailings in simple shear (modified from Daliri et al. 2014, with permission from ASCE) – “ w_d ” denotes water content after desiccation and before resaturation

Figures from CGS Colloquium

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(a)

(b) Days 22, 24, and 27

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(a)

(b)

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Table 1 Types of high density tailings and associated characteristics

	Thickened	Paste	Filtered
Criteria	Non-segregating upon deposition	Can be transported in the laminar range without grain-segregation	Only transportable by conveyor or truck
Typical solids content (mass of solids over total mass)/ Geotechnical water content for hard rock tailings	> 65 % / <54%	> 70 % / 39%	>77 % / < 32%
Yield stress during transport	Generally lower than 50 Pa	> 50 Pa	> 500 Pa – to high to be pumped economically
Water recovery (m ³ /tonne) before deposition, assuming 50% solids slurry exiting Mill	0.45	0.60	0.68

Table 2 Advantages, disadvantages, and uncertainties associated with high density tailings compared to conventional deposition

Characteristic	Advantage	Disadvantage or uncertainties
No water cover	Lower driving head for seepage of contaminants Weight of water not a factor in stability of the tailings or post-failure run-out	Lack of water cover will increase exposure of tailings to oxygen, which may increase acid generation in susceptible tailings
Tailings form sloped landform	Lower dam construction and maintenance costs, OR greater storage capacity for a given dam volume and impoundment footprint if tailings are stacked above crest of dam	Footprint can be large if not constrained by a dam or natural topography Stability of tailings deposited above containment? Prediction or control of the tailings landform / beach slope? Shedding of water from tailings must be managed
Higher density	Increased strength at a given time after deposition Smaller time to trafficability and reclamation	Cost of dewatering and transport
Does not grain size segregate	Homogeneous deposit, with possibly better strength characteristics at a given density Better water-retention characteristics than segregated coarse tailings (Barbour et al. 1991)	Cost of dewatering and transport to segregation threshold

Table 3 Beach slopes reported at selected sites

Site	Deposition rate of solids (t/d)	Solids content (%)	Yield stress (Pa)	Deposition type	Average slope ¹	Climate	Source
Bulyanhulu	2000	72	30-50	Varied location discharge in the impoundment	4.0%	Semi-arid	Addis and Cunnigham (2010)
Kidd Creek	5500	60-65	<10	Central discharge with direction control	2.0%	Wet and cold	Kam et al. (2009)
Musselwhite	4000	65-68	< 10	Varied location Discharge from Perimeter dams stacked upstream	2.0%	Wet and cold	Kam et al. (2011)
Neves Corvo	5500	62-72	30-60	Cycled between 15 cells	2.0%	Semi-arid	Lopez et al. (2013)
Sunrise Dam	9000	59-61	6	Central discharge split into three streams	2.5%	Arid	Seddon and Albee (2015)
Osborne	3700	72-76	20-30	Discharge from advancing cone	3.0%	Arid	McPhail (2015)
Peak	1400	50-55	2	Central discharge split into three streams	2.2%	Arid	Seddon and Fitton (2011)
Ernest Henry	30,000	66-74	<2	Single point discharge to a quadrant	1.0%	Arid	Seddon and Fitton (2011)

¹ Where data was available, the average beachslope is the slope of a cone that would give the same volume for the same footprint as the actual deposit. Otherwise the value reported in the source is given.