Modelling of desiccation and stack geometry in aid of high density tailings deposition

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ABSTRACT
High density or thickened tailings deposition is being trialled by several oil sands operations, as part of their plans to achieve compliance with the new regulations mandated by ERCB. This paper summarizes research undertaken by the authors on both desiccation and the evolution of stack geometry, which has been previously used to interpret high density tailings deposition at hard rock mines. Some general trends are highlighted, and the potential application to oil sands tailings is discussed. This information may prove useful for interpretation of field trails and extrapolation of the results to full scale application.

RÉSUMÉ
Le dépôt à haute densité ou épaissi des residus miniers de queue trialled par plusieurs opérations de “oil sands”, en tant qu'élément de leurs plans pour réaliser la conformité aux nouveaux règlements exigés par ERCB. Ce document récapitule la recherche entreprise par les auteurs sur la dessication et l'évolution de la géométrie de pile, qui a été précédemment employée pour interpréter le dépôt à haute densité de residus miniers produits de queue aux mines d’or et de cuivre. Quelques tendances générales sont accentuées, et l'application potentielle aux produits de queue de “oil sands” est discutée. Cette information peut s'avérer utile pour l'interprétation des traînées de champ et l'extrapolation des résultats à l'application a taille réaliste.

1 INTRODUCTION

Surface disposal of high density or “thickened“ tailings has been applied to many different residuals, including hard rock mining tailings, red muds from bauxite mining, and fly ash disposal. We define “High Density” or HD tailings to denote that the tailings have been sufficiently dewatered such that they exhibit a yield stress upon deposition and therefore will naturally form gently sloping stacks, which do not necessarily require containment by dams. This makes HD tailings deposition an attractive alternative to slurry deposition, due to the significant risk and consequences of dam failure (ICOLD 2001) associated with the latter. HD tailings offer other comparative advantages, including ease of closure due to earlier trafficability afforded by the higher density at deposition, and the benefits of recycling the recovered water. Potential disadvantages include greater exposure to the environment due to lack of water cover, the potential for remobilization of the stack during seismic events (Al-Tarhouni et al. 2009, Li et al 2009), and difficulties in managing deposition geometry (Shuttleworth et al. 2005). The absence of a water cover increases the risk of acid generation in sulphidic tailings (Bryan & Simms 2008), while rain-driven erosion may also be a concern in very humid climates. Directing tailings during deposition to control layer thickness and the overall the geometry of the stack can be difficult due to variability in the rheology the tailings coming out of the pipe, as well as lack of understanding of the overland flow, though this is improving through increased operational experience and research (Shuttleworth et al 2005, Fitton et al. 2008, McPhail 1995, Henriquez & Simms 2009). The technology for dewatering and pumping thickened tailings is now well-established and becoming increasingly cost-effective, as evidenced at the recent international conferences on thickened tailings and associated publications.

The application of HD tailings to the oil sands industry may, in part, serve to meet the new regulations recently established by ERCB, which require a given shear strength in tailings deposits within a certain time after deposition. Many oil sands operations plan to achieve these mandated shear strengths in part by placement of high density tailings, and relying on natural processes, such as: desiccation by drying or freezing, settling, or drainage. The present paper reviews research conducted over the last 5 years on desiccation and on the evolution of stack geometry on cycling deposited high density hard rock tailings. Application to oil sands tailings is discussed, through some generic modelling using expected hydro-geotechnical properties of high density oil sands tailings.

2 BACKGROUND: PROCESSES CONTRIBUTING TO SHEAR STRENGTH DEVELOPMENT

In he context of oil sands tailings, the objective of thickened tailings deposition is quite clear: maximization of density to achieve the regulated shear strength Subsequent to deposition, the density of the tailings will decrease by at least three different phenomena: settling, desiccation, and consolidation. In hard rock tailings, settling can be very significant: For example, in gold tailings deposited at a gravimetric water content (GWC) of ~40%, the void ratio can decrease from 1.4 to 1.0 over 48 hours due to settling alone (Fisseha, 2008). The rate of settling decreases exponentially and can be described as a hindered settling process. In arid climates and for relatively dewatered tailings deposited in thin layers, the rate of settling is quickly overtaken by evaporation; however, in humid climates settling may be very important to densification of tailings. Volume decrease due to settling is likely to be integral to many oil sands operations, especially those that intend to maximize settling through the application of various additives to promote particle aggregation.

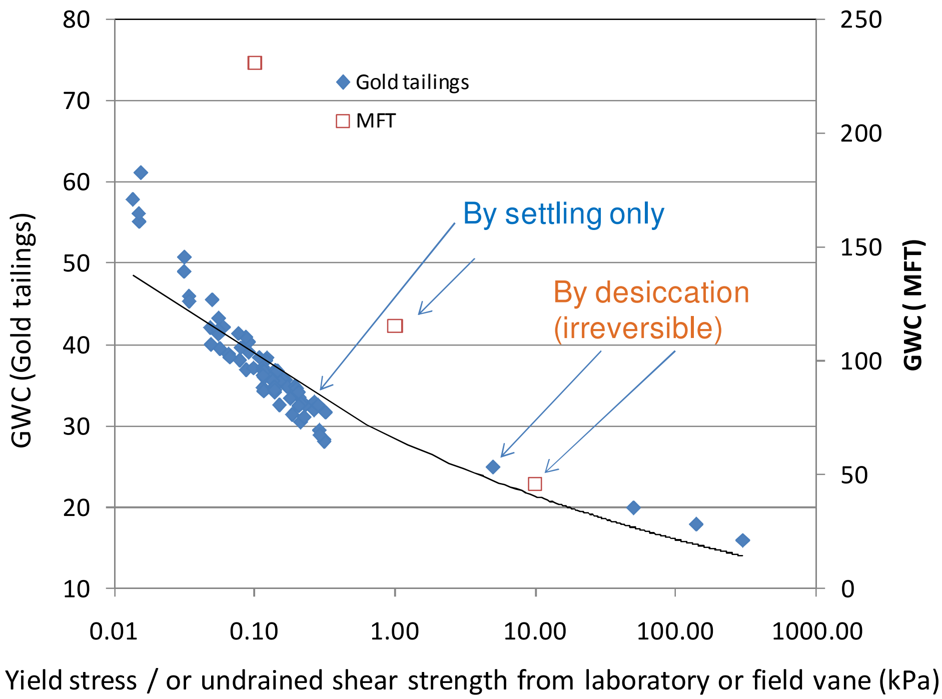

Figure 1. Potential shear strength gain by settling and /or desiccation alone in high density tailings

Figure 1 compares the contribution of settling and desiccation to strength development in a gold tailings and in a thickened MFT tailings produced by the in-line flocculation. For a gold tailings (G_s of 3), the deposition GWC can be as low of 40 % (~70 solids), where the deposition water content for MFT (G_s of 2.6) could be much higher (~3% solids). Natural settling in the gold tailings in the absence of evaporation will decrease the water content to 30%, while a GWC of ~ 120% or void ratio of 3 is a value obtained from one trial of thickened tailings deposition (Jeeravipoolvarn et al. 2009). In gold tailings, the shrinkage limit is approximately ~22%, while the void ratio obtainable by desiccation is at least 1.2 or approximately 50% GWC.

The above numbers speak to the relative contribution desiccation can make for each kind of tailings. Considering a 0.2 m lift, the amount of water required to get from 30% to 22% in the gold tailings is 32 mm, while for the MFT tailings, the amount of water required to get from 120% to 50% is 88 mm.

An important point is the irreversibility of settling and desiccation for both kinds of tailings. While oil sands tailings do contain a significant amount of fines, these fines, however, are mostly composed of kaolinite and illite clay minerals, and therefore MFT has limited capacity to swell. Consider then, if it is dry one day, but rains the next, the precipitation will not reverse the gains in desiccation of the previous day. Thus, analyzing the contribution of desiccation to void ratio decrease in terms of net evaporation as opposed to total will severely underestimate the amount of desiccation-driven volume change.

2. MODELLING DESICCATION

Desiccation is driven by evaporation as well as by seepage into underlying tailings. Evaporation occurring from tailings is similar to classic evaporation behaviour in soils, and can be distinguished by at least two stages.

The first, Stage I, denotes when evaporation occurs at the potential rate, which can be calculated from climatic parameters using the well-known Penman equation or similar expressions. Stage II evaporation occurs when the total suction at the surface reaches a certain value such that the gradient in relative humidity between the soil surface and the overlying atmosphere begins to decrease. Past this point, the rate of evaporation becomes a function of the total suction of the soil surface and decreases below the potential rate (Wilson et al., 1997). The rate of Stage II evaporation depends on a number of factors, including the material properties of the tailings, the relative wetness of the underlying tailings, as well as climate. The various factors affecting desiccation of a fresh lift of tailings are visualised in Figure 2.

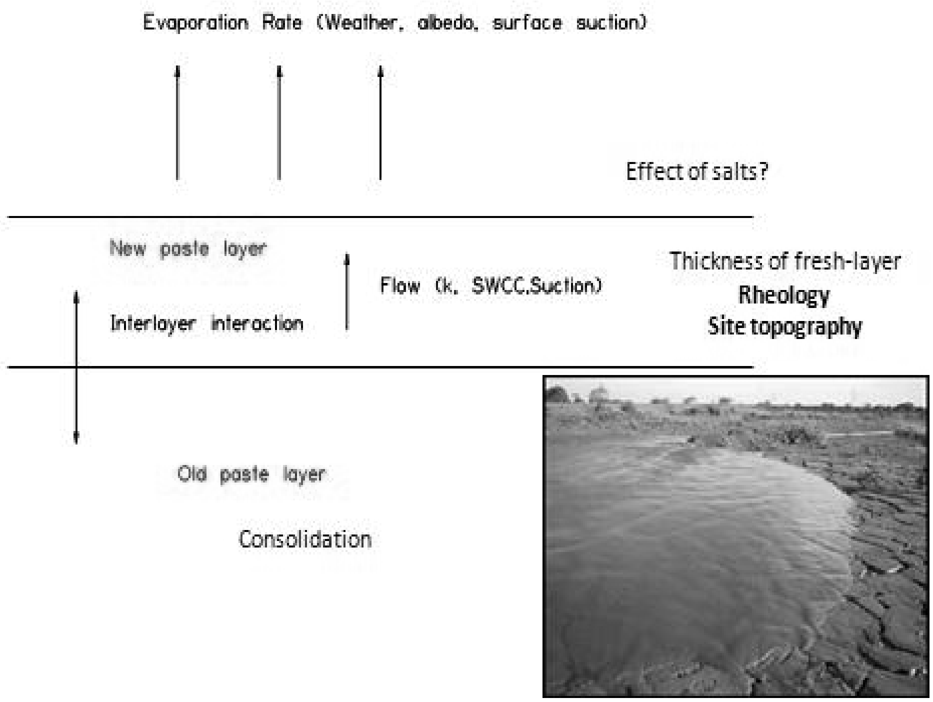

Figure 2. Factors affecting desiccation of a fresh lift of HD tailings (After Simms et al. 2007)

Evaporation and drainage of the fresh layer can be predicted using unsaturated-saturated flow modelling given proper characterisation of the tailings. The use, applicability, and limitations of such models are discussed extensively elsewhere (Simms et al., 2010, 2009, 2007; Fisseha et al., 2010), one important limitation being the suppression of evaporation by salts for tailings that have a high ionic concentration in their pore-water (Dunmola and Simms, 2010; Fujiyasu and Fahey, 2000). Cracking has been shown to be important in very deep slurried deposits, but in the authors' experience the influence of cracking on evaporation from thin lifts of thickened hard rock tailings is minor. While cracking may lengthen Stage I evaporation beyond what is predicted by 1-D unsaturated flow modelling, it does not appear to increase the rate of evaporation beyond the potential rate.

As will be demonstrated, unsaturated flow analysis may help to determine the necessary maximum layer thickness for a given deposition scheme in a given climate: For too thick of a layer, Stage II evaporation may commence at the surface too early, such that the surface of the tailings will dry out, but the mass of tailings in the layer will remain wet and not develop significant shear strength. Also, if the tailings are sufficiently permeable, the underlying stack may actually retard the drying of the fresh layer – evaporative demand from the surface may be satisfied by water withdrawal from the entire stack rather than just from the new lift (Simms et al. 2010). Both these cases are examined in the following analyses, which apply unsaturated-saturated flow modelling to examine two different lift thicknesses for oil sands tailings deposition.

3 MATERIALS AND METHODS

3.1 Materials

Two sets of analyses are performed, one using the properties of MFT, and other using properties of in-line thickened cyclone overflow tailings (Jeeravipoolvarn et al. 2009). We use generic properties of MFT if the data is available or typical properties of low plasticity clays if it is not. The important properties for unsaturated analysis are the shrinkage curve, the water-retention curve (WRC), and the saturated hydraulic conductivity. It is assumed that the shrinkage limit is below the water content corresponding to a void ratio of 1.2, which is reasonable considering void ratios measured in desiccated crusts of MFT. The water retention curves are shown in Figure 3, corresponding to pre-desiccation (after settling) and post-desiccation. For the pre-desiccation WRC, the initial VMC (0.77) corresponds to a void ratio of 3, while the VMC of 0.55 for the post-desiccated tailings corresponds to a void ratio of 1.2. The shape of the water-retention curves are similar to those of low plasticity clays, and can be described by the Fredlund and Xing equation (Fredlund and Xing, 1994), employing the value of parameters *n* and *m* as 1.6 and 0.3 respectively. Saturated hydraulic conductivity values are assigned based on i) For the fresh lift, the average void ratio during deposition, and ii) on the post-desiccation void ratio for the underlying tailings. Two sets of saturated hydraulic conductivity data are used, one for untreated MFT tailings (5×10^{-9} m/s and 1×10^{-9} m/s) or in-line flocculated MFT tailings (1×10^{-7}m/s and 2×10^{-8} m/s). Due to lack of data, it is assumed that the WRC for MFT and in-line thickened tailings are the same.

The reason for using a different WRC for the desiccating and post-desiccated tailings, is the volume change hysteresis of the WRC – these tailings, once desiccated, do not have the capacity to swell back to the original post-settling water content. We assume the WRC starts at the assumed post-desiccation void ratio of 1.2.

Usually it is important to distinguish between two kinds of WRC – one that gives the variation in water content with suction, the other the variation in degree of saturation, S. The latter, in most tailings, must be defined using volume change measured during WRC tests. This latter curve must be the one used to determine the unsaturated hydraulic function when using the built-in methods typically available in unsaturated flow software to predict the relative hydraulic conductivity function from the WRC. Results will be sensitive to this distinction, especially with regard to predicting suction at the surface, which influences the rate of evaporation from the surface and therefore is critical to the contribution desiccation makes to volume change. However, we assume that the shapes of both kinds of WRC are similar for the analyses in this paper.

We do not simulate settling, the assumed initial condition for the fresh tailings is the post-settling solids concentration of 30%.

3.2 Desiccation Simulation

We simulate the desiccation of fresh lifts placed on 5 m of previously deposited tailings. The thickness of the fresh layer is either 0.2 m or 0.5 m. The top boundary condition is the atmospheric boundary condition of Wilson et al. (1997) whereby evaporation rate is coupled to total suction at the soil surface. The bottom boundary condition is either a no-flow boundary condition or a constant head boundary condition of a water table located 1 m below the original ground surface before tailings deposition, where the natural soil is assume to be sand. The initial state of the fresh tailings is the post-settling water content of 30% solids (~77% VWC). It is assumed that the underlying tailings have been desiccated to a void ratio of 1.2, and if any desaturation occurred, the tailings have been resaturated by the water released from settling. Therefore, an initial pore-water pressure of 0 kPa gauge is assumed for both fresh and desiccated tailings. The potential evaporation rate is set to 2 mm/day – this is based on a rough estimation of the average evaporation rate that would occur during non-winter months in Northern Alberta. We employ the unsaturated flow code SVFlux, which automatically optimises time stepping and mesh refinement. The saturated hydraulic conductivity is varied within the range reported in the previous section. Figure 4 is shows the conceptual model for these simulation.

For these kinds of analyses, where a significant amount of volume change occurs, it would be most accurate to change the dimension of the mesh over time. For an initial lift size of 0.2 m, the final lift size would be 0.11 m. For these preliminary analyses, we fix the mesh at the initial lift size.

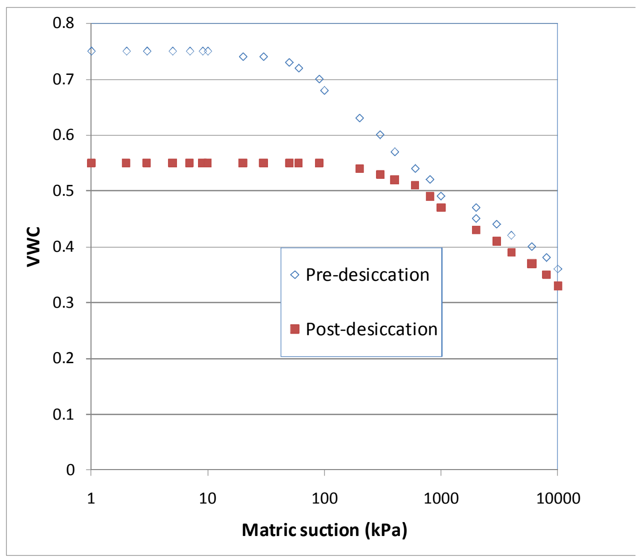

Figure 3. Water-retention curves of tailings

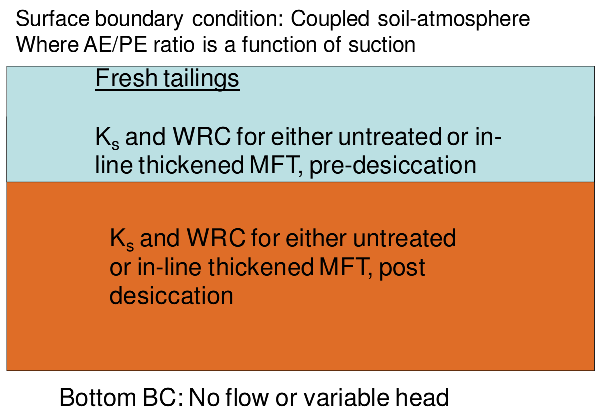

Figure 4. Conceptual model for simulations

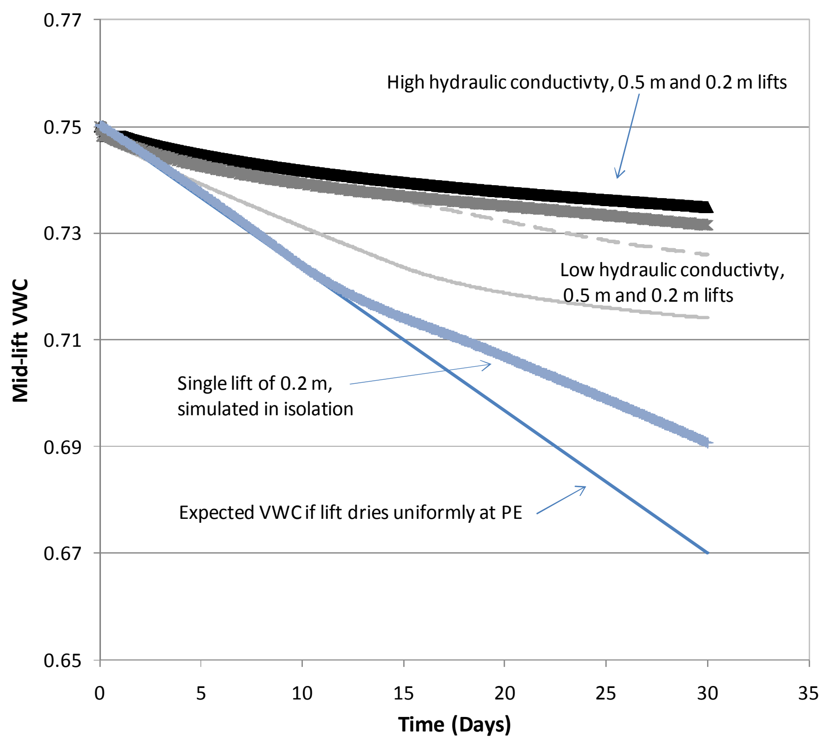

Figure 5. Simulated desiccation of fresh lifts over a month, assumed PE 0f 2 mm/day. Note the target VWC to achieve the mandated shear strength would be 0.55,

4 RESULTS

The simulations of desiccation of a new lift are presented in Figure 5 in terms of a mid-lift volumetric water content (VWC). Also shown is the analysis of a single layer in isolation, in which the underlying tailings are not simulated, and the bottom boundary condition of the lift is set to no-flow. It is clear that the results are very different from what one would expect if the fresh lift dried uniformly at the rate of potential evaporation (PE). The reasons for the difference are two-fold: the decrease in AE below PE due to very high suctions developing at the surface (Stage II evaporation), and the evaporative demand being met by water from the whole tailings stack, not just the fresh layer. The onset of Stage II evaporation is strongly influenced by the hydraulic conductivity of the tailings: for lower saturated hydraulic conductivity, a larger gradient in suction is required to deliver water to the surface to satisfy the evaporative demand, and hence high suctions develop at the surface quicker. The transport of water to from the underlying tailings to the fresh layer also varies with hydraulic conductivity, but is greater for higher hydraulic conductivities. This is illustrated in Figure 6, which shows pore-water pressure (PWP) through the whole depth of tailings. The difference in PWP from the initial condition in the older tailings (0 kPa), correlates to the amount of water contributing to evaporative demand. The higher hydraulic conductivity, the more uniform the distribution of PWP with depth, the greater the amount of water transported upward to the fresh layer.

Another potential “brake” on the contribution of desiccation to volume change is the role of pore-water chemistry, notably the evaporation-driven concentration of ions to the surface and associated salt precipitation. Salts potentially suppress evaporation by a number of mechanisms, including increase in surface reflectivity to infra-red radiation, pore-filling by salt precipitates, and suppression of vapour pressure by the osmotic action of high ion concentrations in the pore-water at the surface. Research on hard rock tailings by Dunmola and Simms (2010a and b) has shown that the suppression of evaporation of salts can be reasonably quantified by the increase in osmotic suction at the surface, which is directly correlated with the pore-water ionic strength. The concentrations of ions, in turn, can be crudely approximated by assuming the ions are concentrated by advection alone, and ignoring diffusion or dispersion (Figure 7). This phenomenon may also be important in oil sands tailings, and could be easily quantified during field trials.

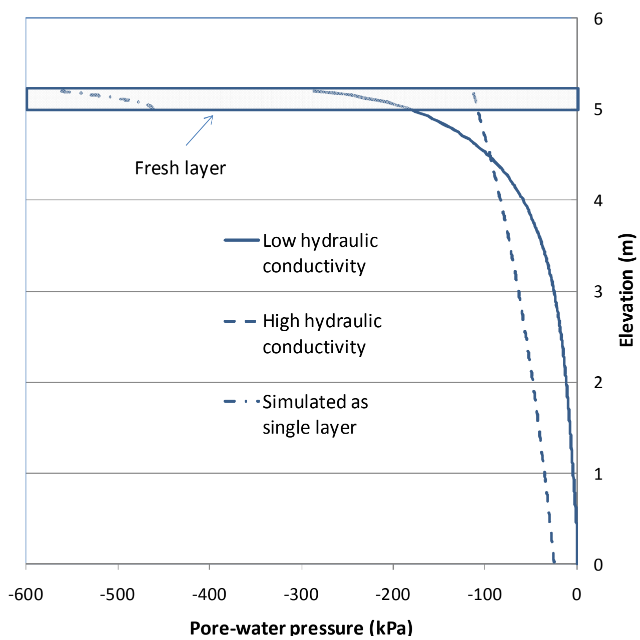

Figure 6. Snap-shot of simulated pore-water pressure distributions during desiccation of 0.2 m lift on top of 5 m previously desiccated tailings

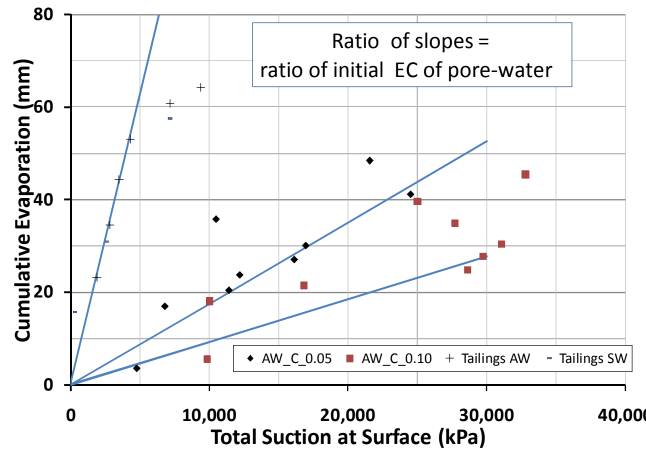

Figure 7. Evolution of total suction at the surface of a desiccating tailings and soils as a function of cumulative evaporation and initial pore-water electrical conductivity.

5 CONTROL OF LIFT THICKNESS

While it is possible to control lift thickness through trial and error by moving spigots and constructing temporary fences or dykes, there are some theories of limited applicability that some might be helpful to deposition management. One such theory is based on “lubrication theory”, which is derived from the Navier-Stokes equations assuming laminar flow, limited inertia, and thin overland flow. These assumptions allow the derivation of equations for equilibrium profiles of a Bingham fluid.
For example, the equation for axi-symmetric deposition over existing topography or over a previous lift of angle θ, with a given yield stress τ_y and bulk density ρ (Yuhi and Mei 2004):

$$h' - h_0' + \ln(1 - h') = x' - x_0'$$

Where:

$$h = h'\left(\frac{\tau_y}{\rho g \sin\theta}\right) \text{ and } x = x'\cot\theta\left(\frac{\tau_y}{\rho g \sin\theta}\right)$$

This equation has been used to predict laboratory-scale flows for hard rock tailings (Mizani et al. 2010, Henriquez and Simms 2009), and has been fitted to some limited field data for fairly dense tailings flows (~70% solids concentration at the pumping water content. Figure 8 shows small-scale simulation of the buildup of a stack, layer by layer. Each layer, after it is deposited, is allowed to fully settle before the next layer is placed, so that is has sufficient strength to resist remobilization during placement of the subsequent layer. At this scale, predictions using Equation 1 are quite reasonable when the density and yield stress of the material at the pumping water content are used. Figure 9 shows data on the evolution of stack geometry during relatively early deposition at a hard rock mine. Qualitatively, the behaviour in Figures 8 and 9 are relatively similar. In general, for thickened tailings site, a "peaking profile" eventually develops, such that the largest angle is nearest to the deposition point, and the angle of the deposit decreases towards the toe. In fact, the angle initially achieved in Figure 9 was not sustained as deposition progressed and the footprint of the tailings associated with this tower grew (Addis and Cunningham 2010).

Figure 10 compares predictions of Equation 1 to the measured geometry of a lift in the field. It can be seen that the best fit was obtained using the yield stress for the tailings corresponding to their post-settling water content. Some evidence (Mizani et al. 2010) suggests that these tailings significantly dewater as they flow away from the deposition point. A very similar behaviour is expected from in-line thickened oil sands tailings, where a very rapid rate of settling will occur.

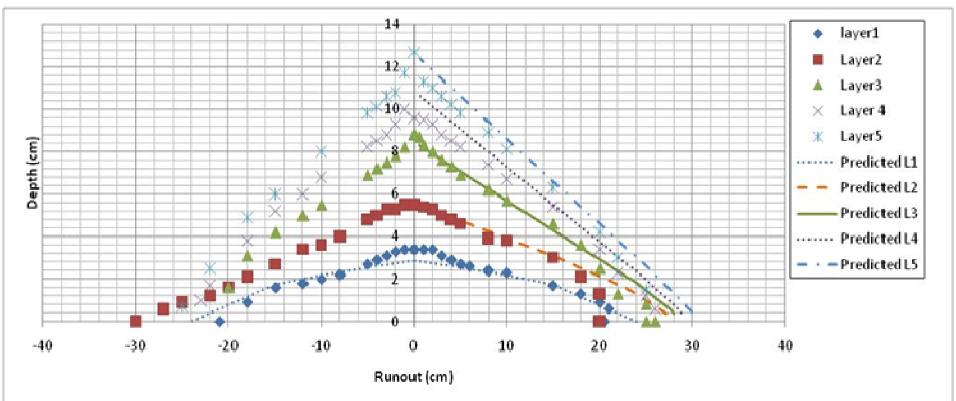

Figure 8. Measured profiles of multilayer deposition of thickened hard rock tailings at the laboratory scale, modelled with Equation 1, using yield stress of 30 Pa and bulk density of 1900 kg/m^3

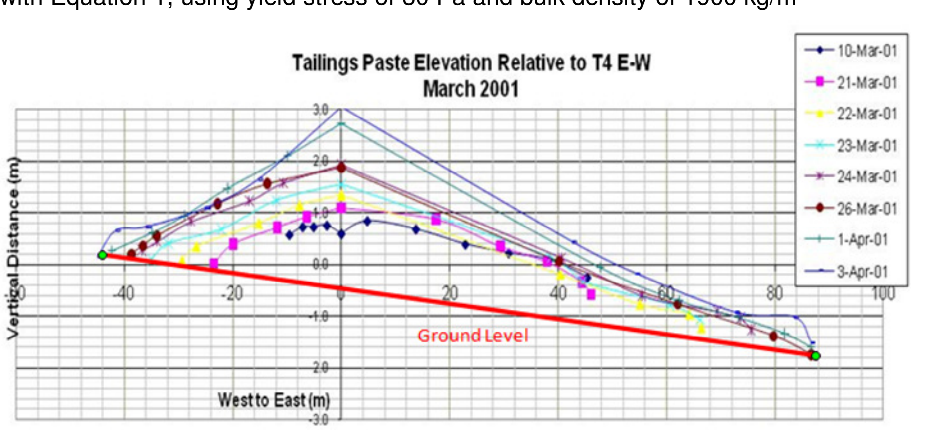

Figure 9. Evolution of stack geometry during early deposition of thickened tailings at a hard rock mine (Crowder 2004)

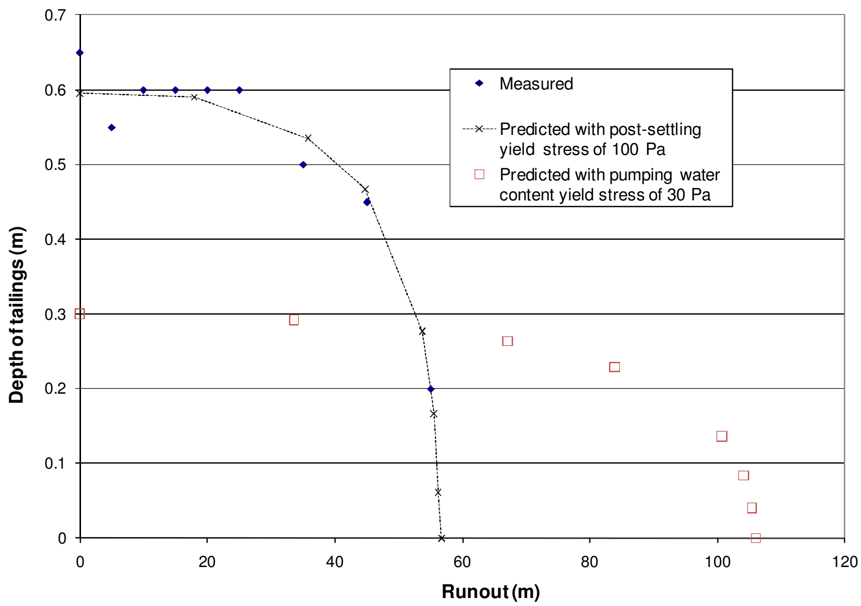

Figure 10 Measured and modelled field lift geometry, the average angle of the underlying tailings was 0.5 degrees.

6 DISCUSSION

Though these analyses are preliminary, it appears unlikely that desiccation alone can achieve the shear strengths mandated by Directive 74, even for in-line flocculated tailings. However, in view of the compressibility data for some MFT thickened tailings (Jeeravipoolvarn et al. 2009), it is apparent that at depths greater than a few metres, thickened tailings can achieve shear strengths of approximately 10 kPa. Therefore, desiccation may only need to be relied upon in the upper few metres of the deposit.

In this case, desiccation can be maximized by a number of measures including: 1. Hydraulically decoupling the upper layers from the mass of tailings, through the use of a capillary barrier (Simms et al. 2010). and 2. Using “mud-farming”, to turn over the material in a fresh lift.

Option 1. Involves placing a thin layer of material of coarse porosity, which induces a capillary break, at a certain level in the tailings profile. This coarse layer could be a coarse fraction of oil sands tailings, geotextile, or natural sand. The capillary break has the additional advantage of stopping transport of ions to the surface. The capillary break concept is well-known in soil cover design.

Option 2. Mud-farming promotes uniform drying of the fresh lift, therefore minimizing the decrease in drying due to the occurrence of Stage II evaporation.

7 SUMMARY

It be should be reiterated that the analyses presented in this paper are preliminary, and that many of the properties used it the modelling were estimated. However, the paper shows the utility of desiccation modelling and the type of useful information it can generate for thickened tailings operations in the oil sands. It is also shown that as lift thickness is an important parameter in thin lift drying, an understanding of the rheology of overland flow of the tailings may also prove useful in managing thickened tailings operations.

Three potential challenges to maximizing the use of evaporation to desiccate the tailings were identified: the reduction in actual evaporation below the potential evaporation rate (Stage II drying), the flow of water from the underlying tailings stack into a freshly placed lift, and the influence of ionic conductivity of the pore-water and associated formation of precipitates at the surface. Two possible remedial measures were identified: the use of a capillary break to stop water and ion transport from underlying tailings, and mudfarming to promote uniform drying in a fresh lift.

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