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Generic modelling of desiccation for cyclic deposition of thickened tailings to maximise density and to minimise oxidation

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Abstract

It has been shown in past publications by the authors' research group that desiccation and desaturation of surface deposited paste tailings can be reasonably predicted using unsaturated flow codes under both laboratory controlled conditions and at a relatively arid field site. Given the variability of climate site to site, and from day to day at any given site, can we make some general guidelines or principles using generic modelling to help guide deposition management? A suite of generic numerical analyses are undertaken in which climate, layer thickness, water retention properties and hydraulic conductivity of the tailings, and water content at deposition are varied. It is shown that considering a single layer in isolation can lead to severe underestimation of drying time required to achieve a given water content or density. The underlying previously desiccated tailings are shown to have a profound influence on the rate of drying of a freshly placed layer, and may indeed make it impossible to reach a given water content through desiccation alone. The use of capillary breaks to overcome this problem is briefly evaluated.

1 Introduction

The potential advantages of surface disposal of thickened tailings compared to conventional deposition are now well recognised: the elimination or reduction of the risk and consequences of dam failure (ICOLD, 2001) associated with the latter, progressive closure enabled by quicker 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 remobilisation of the stack during seismic events (e.g. 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, 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 (Shuttlewoth et al., 2005; Fitton et al., 2008; Henriquez and Simms, 2009; McPhail, 1995).

The technology for dewatering and pumping thickened tailings is now well-established and becoming increasingly cost-effective, as evidenced by the increasing use of the technology reported in this conference series. However, the behaviour of tailings post-deposition is less understood. Evaporation is a particularly important phenomenon, as it may significantly control the performance of the tailings both in terms of shear strength and the quality and quantity of seepage. This paper presents some generic analyses of the evaporation and unsaturated flow in multilayer stacks, building upon the efforts of the authors research group in modelling desiccation of relatively highly thickened gold tailings using conventional unsaturated-flow modelling (Fisseha et al., 2009, 2010; Simms et al., 2007, 2009). While the modelling methodology used in this study have been successfully applied to several laboratory and one field case (as described in the aforementioned publications), the authors advise that some caution should be taken in applying the results of the present paper, and some additional calibration and refinement of the modelling methodology may well be required. Nevertheless, the results are quite interesting and potentially important for management of thickened tailings impoundments.

2 Background

Subsequent to deposition, the density of the tailings will decrease by at least three different phenomena: settling, desiccation, and consolidation. Settling can be very significant, even in tailings deposited as a paste. 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 (Cuthbertson et al., 2008). 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.

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 evaporation from tailings are visualised in Figure 1. Both Stage II evaporation and seepage can be evaluated using conventional unsaturated flow models, given proper characterisation of the tailings. The use, applicability, and limitations of such models are discussed extensively elsewhere (Simms et al., 2007; Fisseha et al., 2009a, 2009b), 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; Fisseha et al., 2009a; 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 highly thickened hard rock tailings is minor.

While unsaturated flow analysis requires some work and care, it is important to establish a 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, therefore limiting the angle of deposition and the overall stability of the stack The results from this study will show an even more dramatic deviation from predictions based on uniform drying of layers.

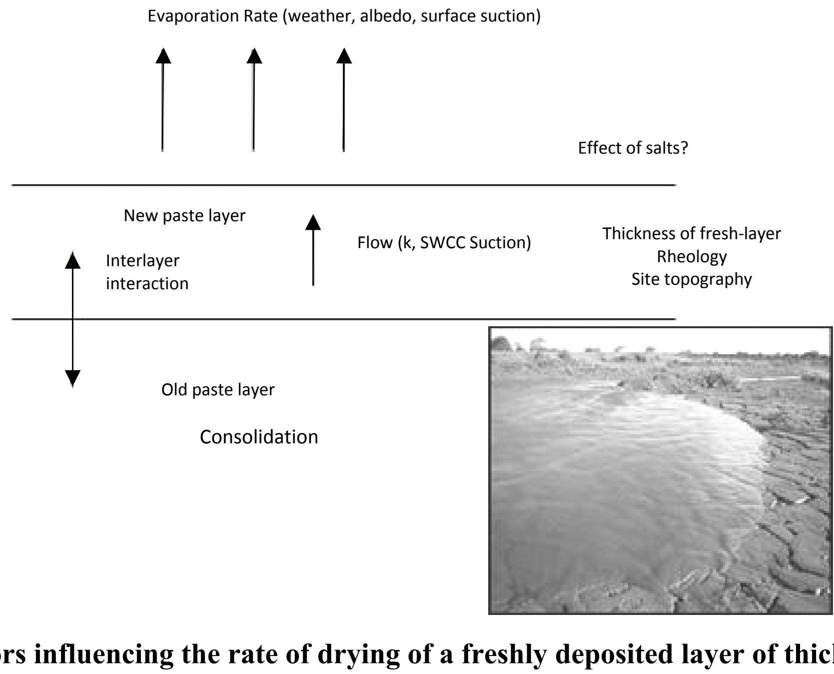

Figure 1 Factors influencing the rate of drying of a freshly deposited layer of thickened tailings (after Simms et al., 2007)

3 Materials and methods

3.1 Materials

For our analyses we use a range of generic tailings parameters. The important properties for unsaturated analysis are the shrinkage curve, the water-retention curve (WRC), and the saturated hydraulic conductivity. The shrinkage curve, WRC, and a typical variation in undrained strength in thickened gold tailings are shown in Figures 2 and 3. The WRC can be fitted by a number of theoretical equations, which use parameters such as the air-entry value (AEV), the slope of the WRC, and the residual water content. In a previous publication (Simms et al., 2009), which examined the sensitivity to AEV of generic analyses of a single layer deposit, the sensitivity of prediction to AEV was small. Therefore, we assume an AEV of approximately 100 kPa, which is a value that is representative of many hard rock tailings (Bryan, 2008; Qui and Sego, 2001). Our WRC is otherwise defined by the Fredlund and Xing equation (Fredlund and Xing, 1994), employing the value of parameters *n* and *m* as 2 and 1 respectively, we also vary saturated hydraulic conductivity between 5×10^{-7} m/s and 5×10^{-9} m/s. This range of values encompasses hard rock tailings as well as CT oil sand tailings (Bryan, 2008; Qui and Sego, 2001; Aubertin et al., 1996).

An important aspect to consider is the volume change hysteresis of the WRC – most tailings desiccated to the shrinkage limit do not have the capacity to 'swell' back to the original water content. Therefore, for tailings that have already been desiccated, we use a WRC that is capped at the gravimetric water content at the shrinkage limit, as illustrated in Figure 2.

Another important point is to distinguish between the two types of WRC – one 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. The true AEV in then taken from the S versus matric suction curve.

3.2 Simulation

We simulate the desiccation of both single lifts and fresh lifts placed on 2 to 8 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 tailings are deposited at a geotechnical gravimetric water content (GWC) of 40% (corresponding to 70% solids for gold tailings), and settling is simulated by using an M_v value of 0.07 and an initial positive pore-water pressure of 1 kPa. The potential evaporation rate is varied between 2 and 10 mm/day. We employ the unsaturated flow code SVFlux, which optimises time stepping and mesh refinement. The saturated hydraulic conductivity is varied within the range reported in the previous section.

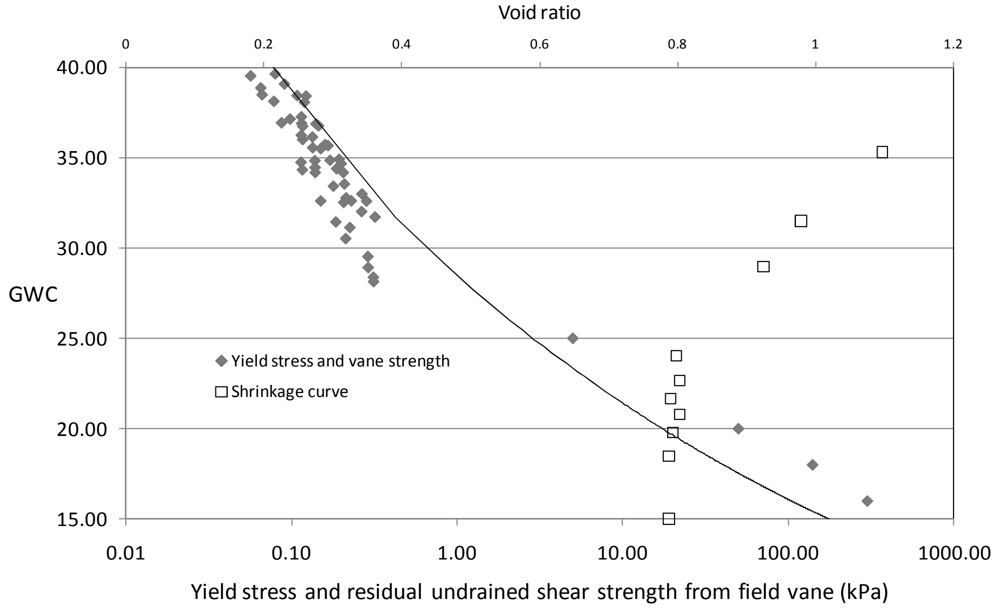

Figure 2 Field vane strength, yield stress from slump, and shrinkage curve of a thickened gold tailings

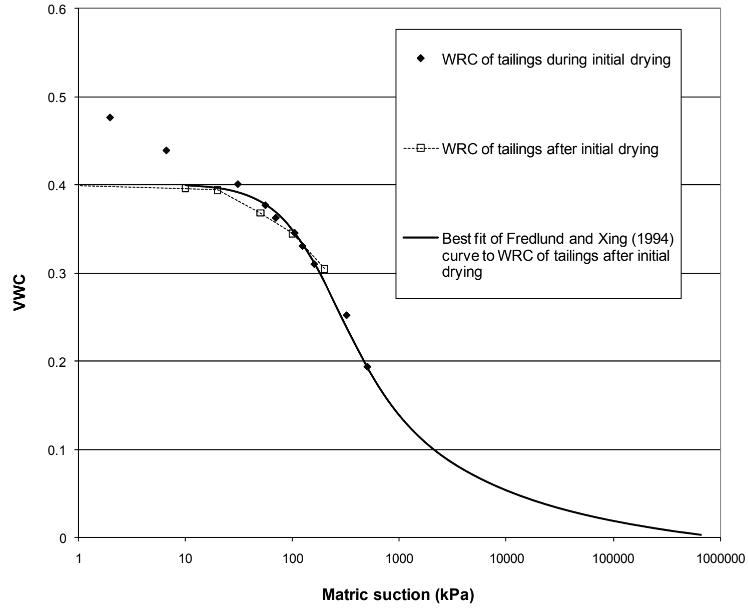

Figure 3 Water-retention curves of a thickened gold tailings during and after initial drying

4 Results

4.1 Simulation of deposition of a single layer in isolation

The results are presented in terms of the mid-point gravimetric water content of the fresh layer. Each results in compared with prediction if uniform drying of a layer is assumed. Figure 4 illustrates the sensitivity of the results to saturated hydraulic conductivity. The lower the hydraulic conductivity, the sooner the onset of stage II evaporation, the sooner the deviation from predictions of uniform drying. The initial drop in GWC data at the onset of drying is due to the simulation of water loss by hindered settling. Figure 5 compares the effect of the bottom boundary condition. The initial rate of drying for the case with a water table below the tailings results in an initially faster rate of drying to some drainage, though both predictions are relatively similar.

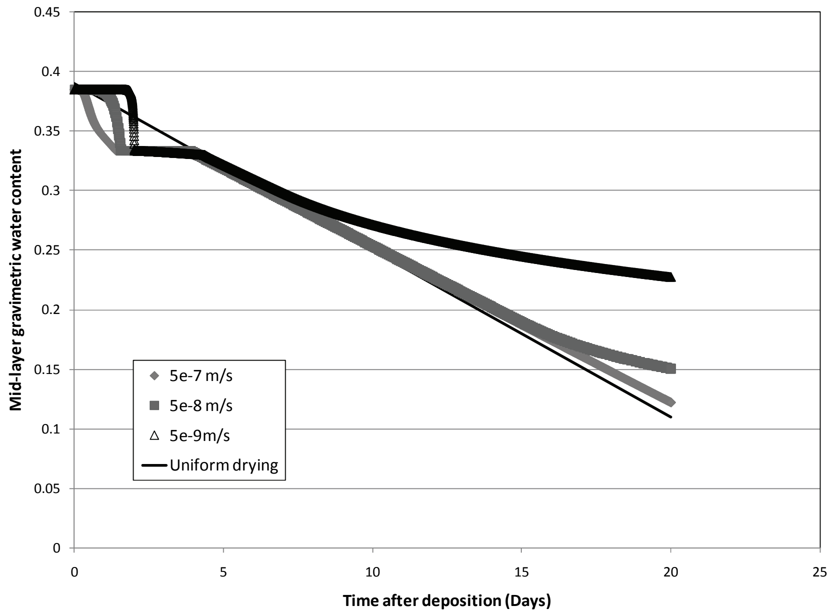

Figure 4 Drying of a 0.5 m layer in isolation under a potential evaporation rate of 10 mm/day for different values of saturated hydraulic conductivity

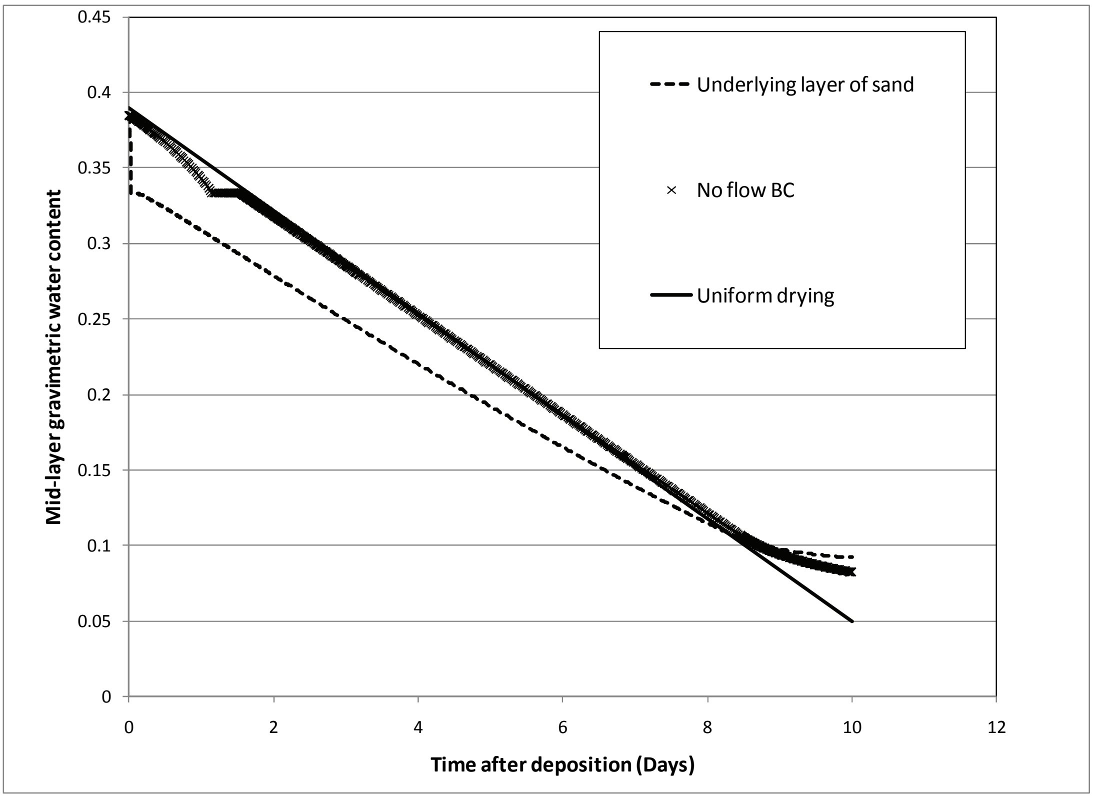

Figure 5 Effect of bottom boundary condition on simulation of desiccation of a single 0.2 m layer, PE = 10 mm/day

4.2 Simulation of deposition on top of deep layer (2–8 m) of tailings

Figures 6 through 8 show various scenarios in which tailings of variable thickness (0.2 or 0.5 m) are placed on top of a variable depth of tailings. Figure 6 shows simulations of drying from 0.5 and 0.2 m thicknesses of fresh tailings placed over a 5 m stack, either in a wet or relatively dry state. 'Wet' denotes that the tailings underneath have gained density by settling only and therefore there is no negative pore-water pressures in the underlying tailings. The relatively dry tailings are assumed to have an initial water content of 20%. This value was chosen, as 20% water content is when significant strength starts to develop in the tailings (Figure 2), but the tailings still have a relatively high degree of saturation (>85%) and so oxidation will be minimal. Figure 7 shows simulation of a 0.2 m fresh layer, where the hydraulic conductivity of the tailings is varied, and the thickness of the underlying layer is varied between 2 and 8. Lastly, in Figure 8, the potential evaporation rate is varied.

From all these results, it is clear that the underlying stack has a very important influence on the drying of the fresh layer. Initially, the fresh tailings may dry faster than a layer in isolation, due to the capillary adsorption of water by the underlying layers. However, once the pore-water pressures equilibriate, evaporation begins to dominate, but now water from the whole stack is supplying evaporation, and therefore the presence of the underlying tailings strongly suppresses the drying of the fresh layer. We see in Figure 8 how the time to achieve 20% GWC is tripled with respect to the assumption of uniform drying for the case with high evaporation (PE = 10 mm/d), and for the next case (5 mm/d) if we extrapolate the results beyond the chart the required drying time is tenfold. Whereas this is 'bad news' in so far of relying on evaporation to drive densification, particularly in wetter climates, we can see that the underlying tailings regulates the drying process, and makes it less sensitive to hydraulic conductivity and stack depth (Figure 7), the thickness of the fresh layer (Figure 6), and even the rate of potential evaporation (Figure 8). In Figure 8, we also show results from a field trial in the summer of 2005 at the Bulyanhulu mine (Simms et al., 2007), in which neither the thickness of the underlying stack nor the antecedent moisture condition were known. The fresh layer had an average thickness of 50 cm and the average pan evaporation rate was 10 mm/d.

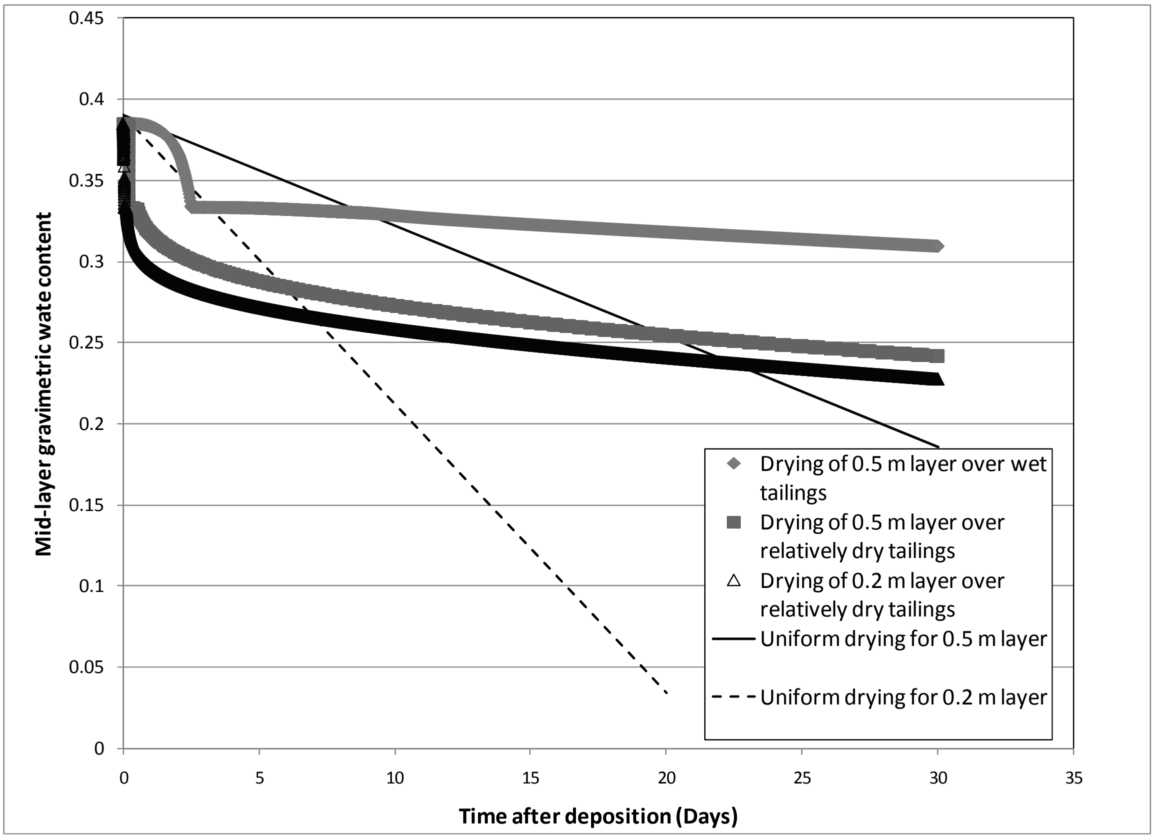

Figure 6 Drying of fresh layer deposited over 5 m of either wet tailings (GWC = 30%) or relatively dry tailings (GWC = 20%), PE = 5 mm /day

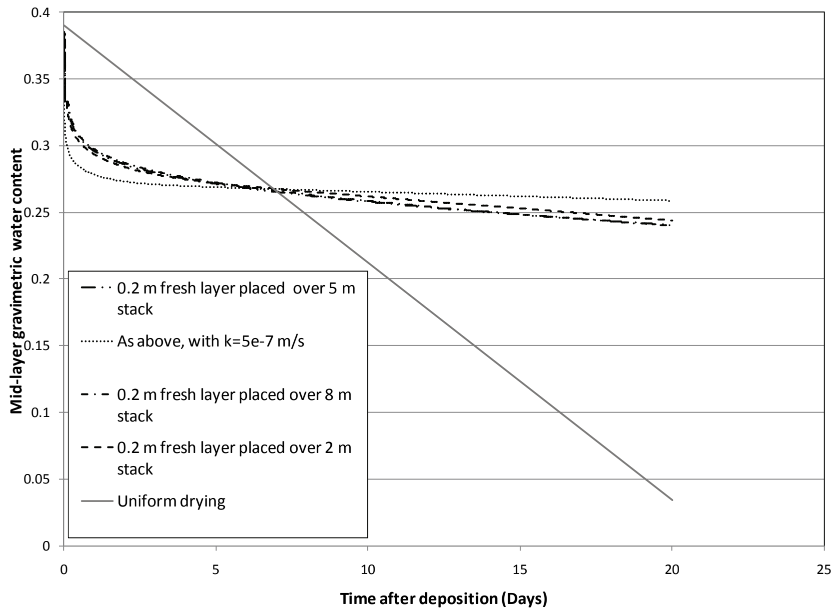

Figure 7 Effect of thickness of underlying layer and hydraulic conductivity of tailings on drying of 0.2 m thick fresh layer, base case hydraulic conductivity of 5e-8 m/s, PE = 5 mm/day

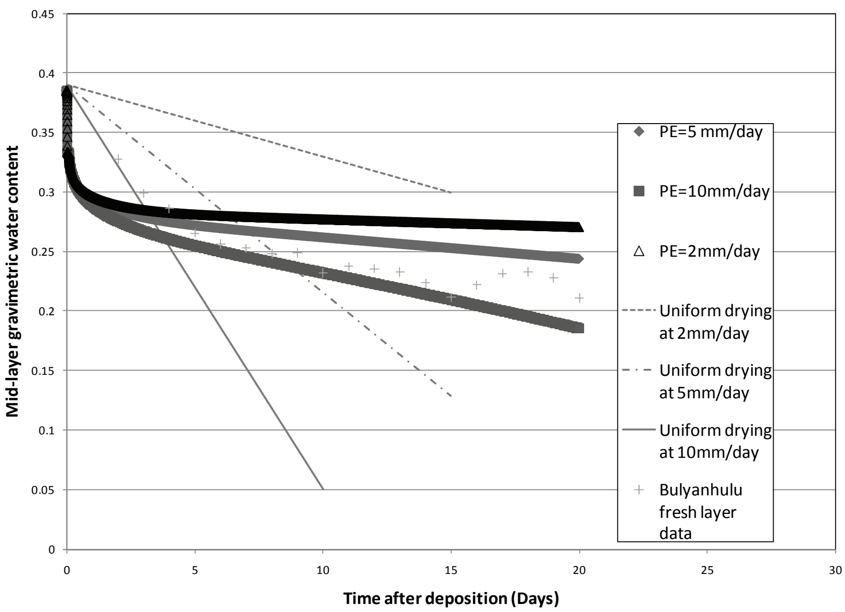

Figure 8 Effect of PE on drying of 0.2 m layer placed over 5 m tailings previously desiccated to 20% gravimetric water content

5 Discussion

The significance of these results to deposition planning is important, especially when one considers that the accumulation of salts at the surface is known to suppress the rate of evaporation in even quite thin deposits of thickened tailings within 20 days (Fisseha et al., 2010). Depending on the desired density and strength, it may not be practical to achieve these objectives by drying alone. On the other hands, these analyses how that any drying below the shrinkage limit occurs very slowly, and therefore the rate of oxidation ingress and oxidation will be relatively low – oxygen diffusion coefficient is strongly dependent on the degree of saturation (Aachib et al., 2004).

However, there are other ways to maximise the work of evaporation. One possibility is to insert capillary breaks between certain numbers of layers to break the connection between the fresh layer and the underlying tailings. This is illustrated in Figure 9, which shows that only a 5 cm layer of fine sand is necessary to facilitate drying of the freshly deposited tailings. It may be possible to derive a material suitable for a capillary break from an operation's waste rock. Filter compatibility and how to place such a layer while the tailings are of relatively low trafficability are issues that would need to be resolved.

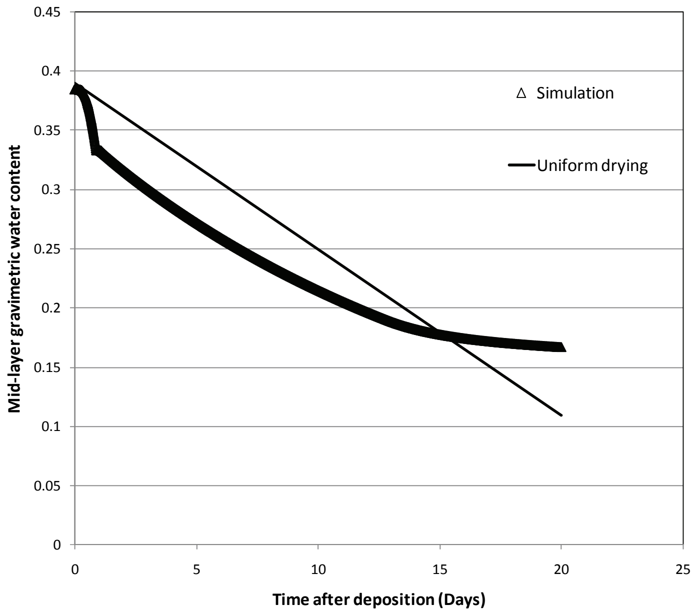

Figure 9 Simulation of 0.5 m layer drying over 5 m thick stack, separated by 0.05 m of fine sand acting as a capillary break

6 Summary and conclusions

A series of generic modelling analyses were undertaken to analyse the contribution of desiccation and drainage to densification in a cyclic deposition scheme. It is shown that predicting drying by assuming uniform drying in a layer, or even performing an unsaturated-saturated flow analysis of a layer in isolation can lead to severe underestimation of drying times. The underlying depth of tailings has a powerful moderating effect on the drying of the fresh layer, which also desensitises the process to variation in potential evaporation and even layer thickness. These results has important implications for operations endeavouring to use atmospheric drying to achieve a given shear strength.

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