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The role of unsaturated soil mechanics in unconventional tailings deposition

Paul Simms[1#]

Article

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Abstract

Desiccation (water loss by drying or freeze-thaw sufficient to generate matric suction), can influence the performance of a tailings deposit both positively and negatively. The significance of desiccation is largest in tailings that have been dewatered prior to deposition, by thickening or filtration. Such tailings can be "stacked" or deposited with a significant slope, which usually implies that a substantial volume of tailings remain above water. Under such conditions the tailings, by accident or by design, may undergo desiccation before burial by fresh tailings. Desiccation can contribute substantially to strength, above and beyond the contribution arising from increase in density, through stress history effects. For some deposits, it is required practice that at least some tailings undergo desiccation to improve, particularly when those tailings for a structural part of a deposit. If, however, tailings remain exposed to the atmosphere in an unsaturated state for some period of time, this may have potential negative consequences through oxidation of sulphide minerals and the formation of acid drainage. This paper describes previous research on the strength gained through desiccation in tailings, and on modelling work that incorporates unsaturated soil phenomena into consolidation analysis. Both types of research are applied to a real field site, providing an example of how novel improvements to tailings management can arise out of application of principles of unsaturated soil mechanics.

1. Introduction

Mining involves the excavation of significantly large volume of rock or soil for purposes of extracting a specific commodity: most often the commodity itself (e.g. gold, copper, bauxite, rare earth metals, etc) is a small fraction of the total volume of geologic material that is processed. Most of this geologic material is combined with large amounts of water to facilitate grinding and /or mineral separation. Due to this reason, mining inevitably results in the generation of large volumes of high water content slurry, with particles size generally ranging from a sandy silt for mining of rock, to finer particles containing clay minerals when the parent material is a soil (such as for bauxite or oil sands operations). In all cases, the tailings are transported as a high water content slurry between different operations in the mill (Willis, 2006). At the majority of mines, the tailings are deposited directly into a dammed impoundment, where the water content is usually at least twice their liquid limit (Vick, 1990). New mines show a trend of increasing production rates, and mines that process over 200,000 m^3 of rock a day, with mine lives in the order of decades, are becoming more common. Such rates of mining results in large tailings deposits, often covering several square kilometres, with dam heights in certain scenarios reach up to 400 m. The dams of impoundments themselves are some of largest earth structures in the world.

Unfortunately, tailings dams fail with some regularity, at a rate of 4 or 5 a year. Some of these failures have resulted in loss of life and up to billions of dollars in damage to property and / or associated environmental cleanup costs (Rico et al., 2008). This includes the well-known failure at Brumadinho in Brazil, which killed about 300 people in 2019. Other failures of significance that have been analyzed in the geotechnical literature include the Mount Polley failure in Canada in 2014 (Zabolotnii et al., 2021), the los Frailes dam failure in 1998 in Southern Spain, and the Merriespruit failure (Fourie et al., 2001). Tailings dams fail for a variety of reasons, including poor foundation conditions, poor water level control, and damage due to seismic events. Industry response to these failures has been twofold: either to improve the level of care afforded to tailings dam design and maintenance through changes in regulation or management culture, or to implement

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[#] Corresponding author. E-mail address: Paul.simms@carleton.ca
[1] Carleton University, Department of Civil and Environmental Engineering, Ottawa, Canada.

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technologies that improve the geotechnical performance of the tailings themselves.

The most common alternatives technologies involve dewatering the tailings to some degree before deposition, either by thickening in large (> 20 m high) thickeners, or through filtration, which facilitates quicker consolidation. Often, such thickened or filtered tailings are transported by pipeline, conveyer, or truck, to various points in a tailings impoundment. As the dewatered tailings possess a small undrained shear strength (< 1kPa and often measured using rheometry and referred to as a yield stress) at their initial state out of the pipe, they will naturally stack (Mizani et al., 2013; Henriquez & Simms, 2009) and form discrete layers. This allows for evaporation to assist in further dewatering and densification of the tailings, before deposition cycles around again and those tailings are buried (Simms, 2017). An example of such a deposit is shown in Figure 1, where the deposition point is changed every 2 weeks, such that one circuit of the embankment is completed each year. Figure 2, from a different site, shows the difference between older more desiccated tailings, and a younger layer deposited on top.

How such deposition schemes are conducted are typically based on the operator's experience. This paper will show that hydro-mechanical analysis, which includes consideration of unsaturated soil mechanics, may provide helpful guidance to these types of operations.

Figure 3 indicates conceptually the progress of dewatering of a given layer of thickened or filtered tailings. Initially, the tailings dewater through sedimentation and consolidation. Depending on the commodity and the extent of initial dewatering, deformations at this stage are large: void ratios reduce from values above 2 (sometimes as high as 5) to close to 1. Simultaneously, the upper part of the layer may begin to desaturate. With the addition of a new layer, several behaviours will manifest, including the effect of additional weight on the previously desiccated tailings, the acceleration of consolidation of the new layer due to rewetting occurring in the bottom layer, and the potential for wetting-induced collapse in the previously desiccated lower layers.

The hydro-mechanical evolution of a tailings deposit is therefore somewhat complex. The reader may wonder if indeed it is worthwhile to consider this complexity. It may well be worthwhile, for two main reasons. The extent of desiccation or desaturation is important to the tailings impoundment: desiccation leads to an increase in strength through multiple mechanisms, however, if a layer of tailings becomes desaturated and remains so for an extensive period of time there may be a potential risk of acid generation. The paper proceeds by i) briefly reviewing the positive and negative effects associated with the unsaturated behaviour, then; ii) providing some data from large laboratory experiments and the field on multilayer deposition of tailings; and finally; iii) showing examples of numerical simulation of a field site.

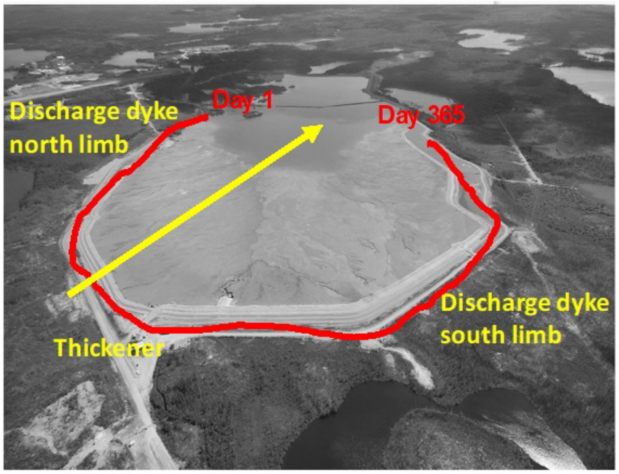


Figure 1. Example of a thickened tailings deposit, where deposition is cycled from different points on a perimeter embankment – here the circuit is complete in 1 year.

Figure 2. A thickened tailings site, where a relatively fresh layer can be distinguished from the underlying desiccated layer (Courtesy Jason Crowder).

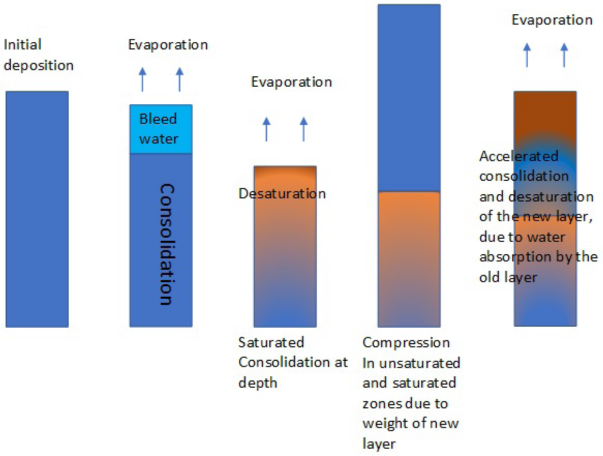


Figure 3. Phenomena contributing to post-deposition dewatering in layered tailings deposits (modified from Qi & Simms, 2018).

2. Desiccation and its consequences for strength and acid generation

2.1 Strength

Desiccation imparts additional strength to tailings by i) contributing to higher density; ii) an increase in effective stress through matric suction, that would be dissipated if the tailings are re-wetted; and iii) stress history effects. The last effect is most relevant to the contribution to strength by desiccation to tailings that are subsequently buried and rewetted. In the scientific literature, the stress path experienced by the tailings has been explored for relatively thin layers (100 mm to 300 mm), where samples are allowed to desiccate, are rewetted to eliminate matric suctions (by application of water until ponding is observed and/or measured suctions are dissipated), and then samples are either trimmed or extracted using thin-wall tubes, and subsequently tested in simple shear or tri-axial devices (Al-Tarhouni et al., 2011; Daliri et al., 2014, 2016). Trimmed samples are usually obtained from short columns (~ 100 mm); samples extracted using thin-walled tubes are extracted from large (1m by 1m in plan) physical simulations of multilayer deposition (drybox tests). An example of sampling from one of the larger multilayer drybox tests is shown in Figure 4.

The samples obtained from the columns or drybox tests are trimmed and placed in element testing apparatus, where they are subsequently consolidated before shearing. This generates a stress path that comprises initial sedimentation, consolidation, desiccation, rewetting, and then consolidation, the last simulating burial of a layer of tailings by a substantial thickness of newer tailings. Subsequent results are shown for a gold tailings with the following properties: Specific gravity, liquid limit, plastic limit, and shrinkage limit were determined as 2.89, 22.5%, 20%, and 18% respectively; while the D_{90}, D_{50}, D_{30}, and D_{10} values are 120, 30, 12, 1.5 µm, respectively. Figures 5 through 7 show the Water-retention curve / soil-water characteristic curve (WRC), examples of stress paths before shearing, and the results of constant volume simple shear tests in terms of shear stress and strain. In terms of stress path

Figure 4. Drying box test (1m × 1m in plan) showing extraction of samples with thin-walled tubes (from Daliri et al., 2016).

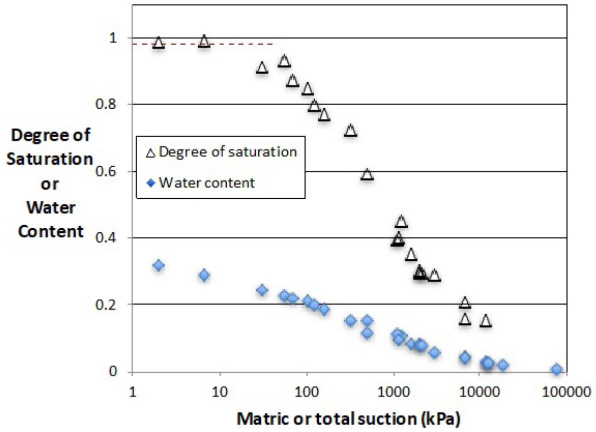


Figure 5. WRC of the gold tailings samples shown in subsequent figures, obtained by conventional axis-translation for suction below 500 kPa, and paired measurements of total suction (Dewpoint Hygrometer) and water content for higher measurements.

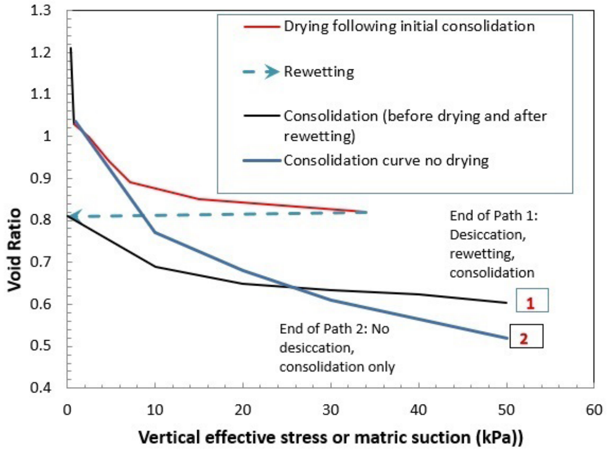


Figure 6. Example of stress paths imposed on laboratory samples before element testing.

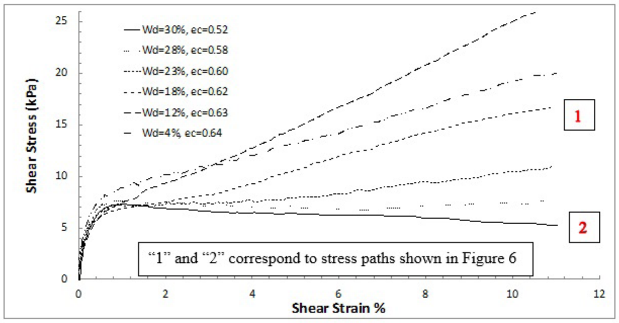


Figure 7. Shear strength in constant volume simple shear of gold tailings desiccated, re-wet, and then consolidated to 50 kPa. "Wd" is water content after initial desiccation but before rewetting, "ec" is the void ratio after rewetting and consolidation to 50 kPa.

(Figure 6), the most interesting finding is that the previously desiccated samples are less compressible than samples that have never been desiccated (virgin material). Similarly, Figure 7 shows that as the initial degree of desiccation increases, the tailings exhibit greater degrees of strain hardening, built only up to a point - the amount of strain hardening in the sample desiccated to 4% water content, is less than the strain hardening for the sample desiccated to 12%. Figure 7 also shows that the desiccated tailings are stronger despite having higher void ratios than the virgin tailings.

These results conform qualitatively to expected elasto-plastic behaviour in unsaturated soils, in that suction will contribute to strength through expansion of the yield surface. However, the more common elasto-plastic formulations of unsaturated soils are not concerned with the manner of strength increase shown in Figure 7, that is an increase in dilation. Most elasto-plastic unsaturated soils models aim to emulate behavior observed in clayey soils: on a strength basis, this is expansion or contraction of yield surface that produces a peak strength declining to a residual value at large strains. Therefore, quantitative explanation of the behaviour shown in Figure 7 is a potential avenue for future research.

In terms of practice, the changes in shear strength behaviour are quite significant. The behavior of the virgin sample (no desiccation) shows strain softening behavior, that is, the strength decreased with strain. It is thought that this behavior is associated with long runouts and their associated catastrophic effects (e.g. Fourie et al., 2001).

Another way to represent the influence of desiccation on strength is through field vane measurements. Figure 8 shows vane shear strength data for thickened gold tailings from both drybox tests shown previously as well field data from near surface measurements at two gold mines. The data from Musselwhite is collected and presented by Kam et al. (2011). The vane measurements show similar trends to the element shear strength, in that the desiccated –rewet samples show a maximum value as degree of desiccation increases. For comparison, the peak strength from the simple shear test in Figure 7 for the un-desiccated sample is shown, using the water content of the consolidated sample, which gives a sense of the magnitude of the suction-related effects on strength. Figure 8 also shows how the field measurements are potentially influenced by both current matric suction values, and also by stress history. The range in the Musselwhite data suggests that some of these measurements are influenced by matric suctions that are present during the vane measurements, while the values on the low end likely represent stress history effects only, presumably taken during wetter conditions after the dissipation of matric suctions. Figure 8 clearly shows the relevance of unsaturated soil mechanics in interpreting conventional measurements, as for some sites, such field vane measurements are used to judge the timing of embankment raises, when these are partially constructed on top of the tailings., and the strength of the tailings themselves are critically important. Clearly the stress history effect is the most reliable and the key contributor to shear strength out of all the possible contributing effects of matric suction (which include lower density, present suction values, stress history).

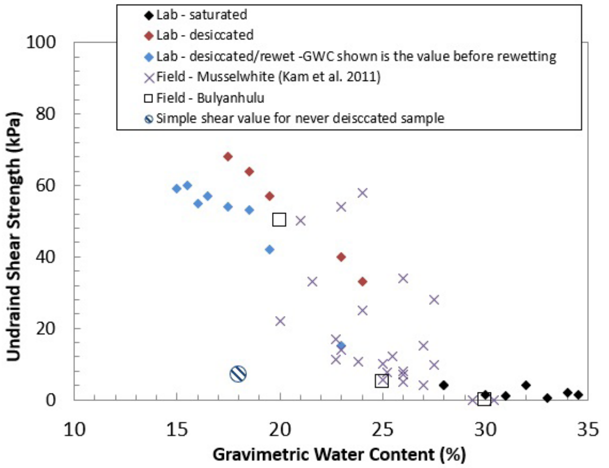


Figure 8. Influence of desiccation and subsequent rewetting in laboratory and field shear strengths for gold tailings from two mines (Bulyanhulu and Musselwhite) as measured by a shear vane.

2.2 Desaturation and potential for acid generation

The major negative potential impact of desiccation on tailings performance is the increased risk of acid generation, which occurs via oxygen transport into the tailings, the oxygen serving as the principal oxidant to dissolve certain minerals that are unstable under oxidizing conditions. The dissolution of some of these minerals, the most common being pyrite (FeS_2), results in the generation of very low pH water, which in turn leads to the dissolution of other minerals, eventually generating water with low pH and very high concentration of dissolved mass. This water is termed acid drainage, and its generation and its effects have been studied for many decades, the following reference list far from being exhaustive: Aubertin et al. (2016), Simms et al. (2000), Blowes & Jambor (1990), Singer & Stumm (1970).

In terms of unsaturated soil behaviour, the key parameter is the degree of saturation, which governs the effective diffusion coefficient of oxygen into the tailings. There are a set of different equations to predict the variation in oxygen diffusion with saturation (Aachib et al., 2004), but they all plot quite close to the relationship shown in Figure 9. In thickened or filtered tailings deposits, acid generation seems to occur only if i) there is a sufficient quantity of acid generating minerals, ii) significant desaturation occurs (degree of saturation < 0.8), and iii) the tailings remain at this low saturation for at least a month. References to specific sites is given in Simms (2017).

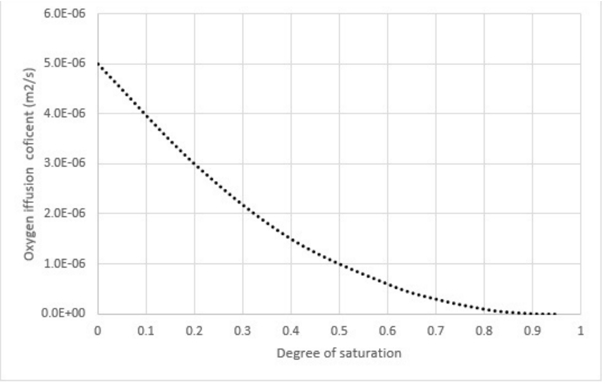


Figure 9. Variation of oxygen diffusivity with saturation using Millington-Quirk model.

3. Predicting the variation in void ratio, stress, state and degree of saturation in a given tailings deposition plan

3.1 Theoretical concepts

The preceding text has shown that the effect of desiccation can be positive in terms of strength, but there is some risk to increased poor geo-environmental performance due to sulphide mineral oxidation. Therefore, hydro-mechanical analysis of potential tailings deposition plans, or analysis of existing operations or pilots with the view to optimization, would be valuable to assist mines to maximize performance of their tailings deposition operations.

As shown in Figure 3, several simultaneous and coupled processes influence volume change and desaturation in a multi-layer deposition scheme. The most rigorous analysis therefore requires consideration of large strain consolidation, unsaturated flow with dependency of constitutive relationships on both density and degree of saturation, and considerations of yield surface effects by both mechanical and hydraulic loading. Fortunately, there exists a significant literature on the elasto-plastic behavior of unsaturated soils, with associated soil models such as the Basic Barcelona Model (BBM), the modified state surface model (MSSM), the Glasgow coupled model GCM), and several others (a recent summary is presented by Qi et al., 2020). These models, however, have been applied in the context of buffer design for nuclear waste repository. The application to tailings requires is for generally lower range of total stress, and additionally, the deformations of tailings can be large, which requires a large strain consolidation analysis.

This author and his colleagues have developed the UNSATCON model, which is designed to analyze this kind of tailings deposition scheme. The model combines large strain consolidation with the aforementioned elasto-plastic soil models, using the piecewise-linear approach to large strain consolidation developed by Fox & Berles (1997). This model and its applicability to field cases and laboratory studies for monotonic dewatering is presented in Qi et al. (2017a, b), while the addition of elasto-plastic unsaturated soil models in described in Qi et al. (2020). The authors have subsequently implemented several of the aforementioned elasto-plastic constitutive models for unsaturated soils in the UNSATCON platform, including:

i) the modified State Surface Method (SSM) proposed by Zhang & Lytton (2009) coupled to a simple void ratio dependent water retention curve;
ii) the well-known Barcelona Basic Model (BBM) (Alonso et al., 1990). coupled to the same simple water retention model;
iii) the SSM and BBM models coupled to bounding plasticity water-retention model of Gallipoli & Bruno (2017); and
iv) the Glasgow Coupled Model (GCM), first proposed by Wheeler et al. (2003)

The UNSATCON framework incorporating these various elasto-plastic unsaturated soil models has been tested on the multilayer drybox type tests described in the first section for different types of tailings (Qi, 2017; Qi et al., 2020). When calibrated to the same basic material parameters, these models give similar global results when analyzing multilayer tailings deposition, though there are some differences that may have important implications considering large deposits. For example, GCM type models consider the influence of cumulative plastic strain due to repeated wetting-drying cycles, which cannot be considered by some other models. The difference between models is explored in detail in Qi et al. (2020), and will not be repeated here. Rather, this paper will focus on the general behaviours of such models and the associated practical implications for tailings deposit simulation.

The material parameters required for this type of analysis are the saturated large strain consolidation properties (hydraulic conductivity as a function of void ratio, and void ratio as a function of vertical effective stress), and the water retention curve/soil-water characteristic curve. If the latter is measured with a standard axis translation test where volume change is measured, that information is sufficient to calibrate the unsaturated parameters of the models.

The key components of the analysis are a generalized set of functions to describe volume change, and a volume change dependent water retention curve. The generalization of the volume change relationships is shown Figures 10a and 10b, the former being simply the standard formulation for saturated soils. In 10b, stress history effects can be both from suction or stress, causing the elastic surface to move low values of void ratio and so progressively change the yield surface. Put another way, 10b combines the shrinkage curve with the compressibility function to define the 3D volume change surface.

The physical relevance of this to tailings deposits, is that if a layer of tailings experiences substantial desiccation, due the high suctions, that layer of tailings will likely remain in the elastic region with respect to volume change for a considerable thickness of overlying tailings. For example, if the void ratio corresponding to virgin compression under 100 kPa matric suction is in the neighborhood of the same

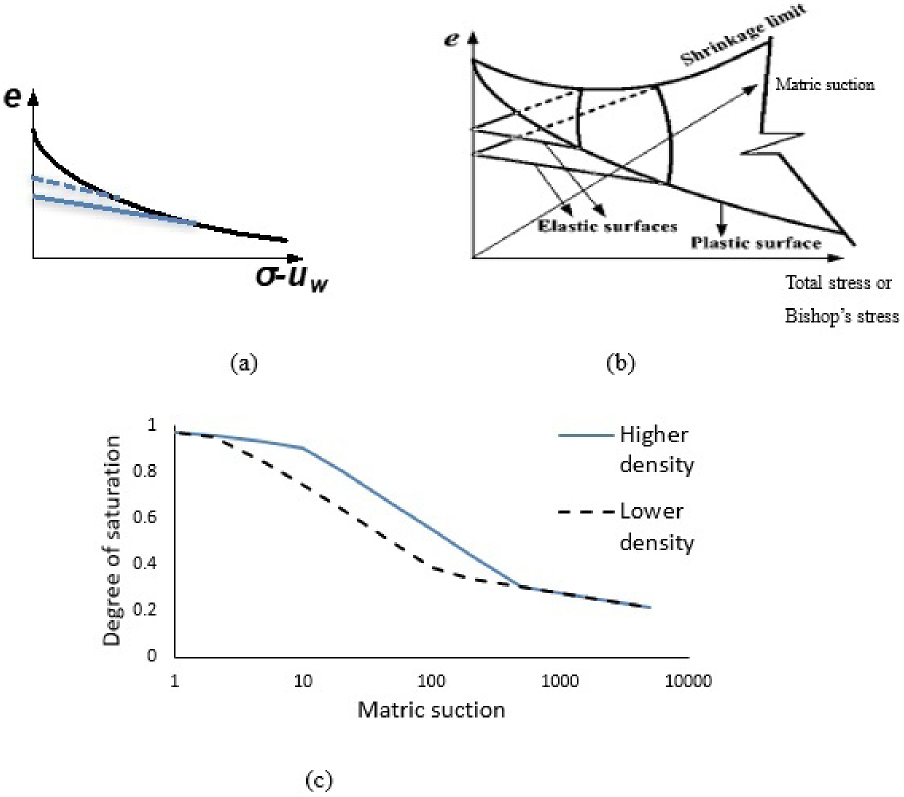


Figure 10. Representation of the key concepts for hydro-mechanical coupling (a) unload-reload behavior in a saturated soil; (b) generalization of this behaviour to unsaturated conditions, where the elastic and plastic constitutive functions are now dependent on two variables; (c) void ratio dependency of a water retention curve.

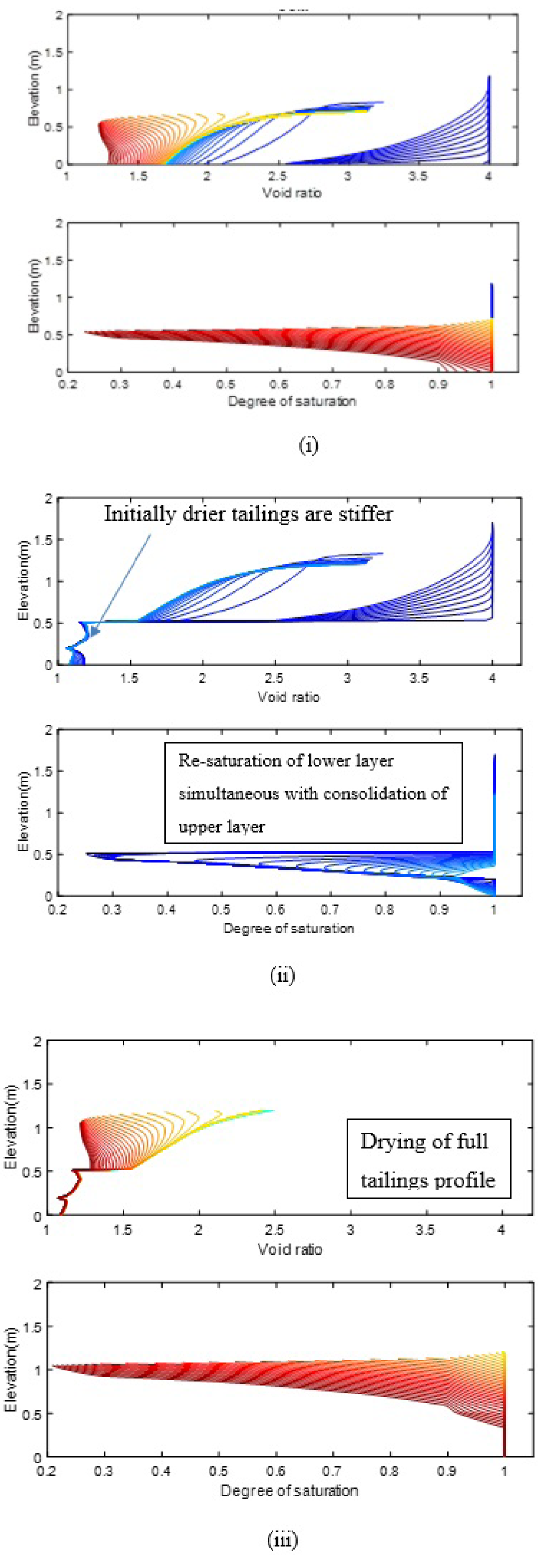
value of total stress for 70 kPa, this will mean that it could require burial by 5 m for volume change to reach again to the plastic surface. Put another way, essentially desiccation can lead to substantial pre-consolidation pressures in the first layer, that will not be succeeded by either future drying, and not be loading until substantial thickness of tailings are deposited. This situation is most relevant for hard rock tailings, for their comparatively lower hydraulic conductivity generates a more uniform distribution of matric suction.

Figure 10c illustrates the dependency of the WRC on void ratio. The dependency of the air entry value on void ratio is particularly important to water exchange between fresh and old tailings. Having a softer tailings will allow for greater contribution of evaporation to volume change as opposed to desaturation, which will allow for greater strength and less risk of acid generation.

Figure 11 shows detailed outputs from analysis of relatively soft and clayey tailings. The tailings initially undergo self-weight consolidation, reaching a typical profile of void ratio vs depth by the yellow line. Thereafter, after the rate of bleed water generation drops below the evaporation rate, the tailings begin to desiccate and subsequently desaturate, the lowest void ratio being reached at the surface (here nearer the shrinkage limit), the tailings at the bottom reaching lower matric suctions corresponding to higher degrees of saturation. With the placement of the new layer there is a visible compression in the underlying tailings, as the bottom tailings are still largely saturated, and have not experienced the same degree of desiccation, are softer, and therefore compress more under the weight of the new tailings. Eventually, after the second layer consolidates (accelerated by adsorption of water by the bottom layer), the whole profile undergoes evaporation. The final void ratio profile is not only a function of variation in load, but it also influenced variation in stress history, as the yield surface (Figure 10b) is at different locations for different depths.

3.2 Example application to a field site

To highlight the significance of the elasto-plastic unsaturated behaviour to practical applications, the following describes in brief the analysis of real thickened tailings site in Northern Ontario, Canada. Tailings are deposited at gravimetric water contents of approximately 50%. The deposition rate (volume of the tailings as they come out the end of the pipe / divided by the impoundment footprint) is about 2.5 m per year. The tailings are deposited from various spigots, using the same deposition scheme shown in Figure 1, Deposition covers the whole area in roughly 1 year.



(i)

(ii)

(iii)

Figure 11. Example of UNSATCON outputs simulating deposition of two layers (i) Initial self-weight consolidation to yellow line, thereafter drying once evaporation rate exceeds bleed water generation; (ii) initial compression and short term interactions after placement of new layer; (iii) eventual second drying phase.

The climate in northern Ontario, Canada is relatively cold and wet. Figure 12 shows gravimetric water contents measured in the field near the surface of a thickened tailings. The figure is annotated to show the water content at deposition. It is clear that there are two trends, one for late Fall or Spring, where the evaporation rate is very low, the other for Summer where the evaporation rate is substantial. From May to September, the average potential evaporation rate is ~ 1.5 mm/day.

The UNSATCON model was employed to analyze this data (Qi & Simms, 2018). A column test was used to back calculate the large strain consolidation properties, and a water–retention curve was measured, which was sufficient to calibrate all the properties. A modified state surface model was employed to simulate the elasto-plastic behaviour. Of significance, the hydraulic conductivity function for this site is relatively high ($5 \times 10^{-6}\, e^4$ m/s). The model was run over a range of plausible rates of rise (the one-dimensional rate of filling, assuming no water release after deposition), to examine whether the model could reproduce the field data, and then to examine sensitivity of performance to deposition rate.

The modelling results are shown in Figures 13 and 14 for three different deposition rates (2, 2.5 and 3 m per year),

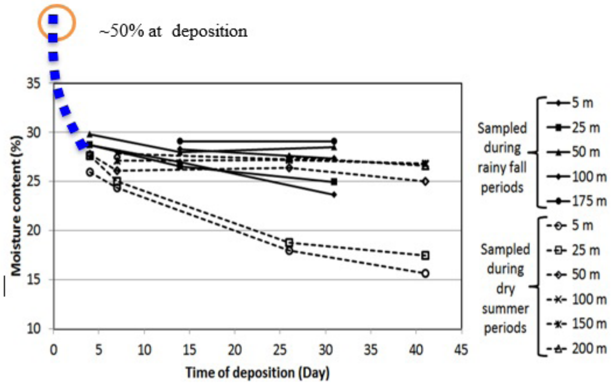


Figure 12. Gravimetric water contents samples at a thickened tailings site. Data from Kam et al. (2011). Distance in legend refers to distance from deposition point.

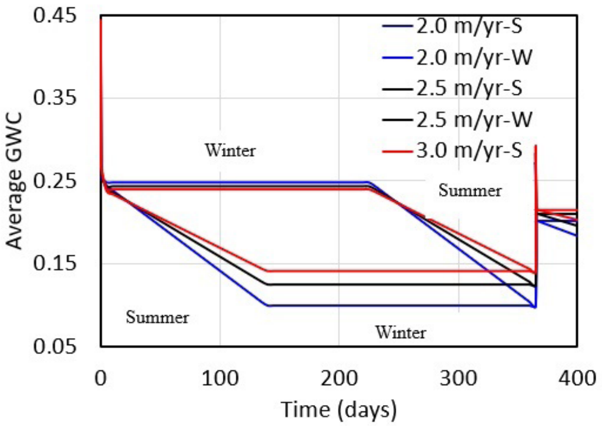


Figure 13. Simulated average GWC in the first layer.

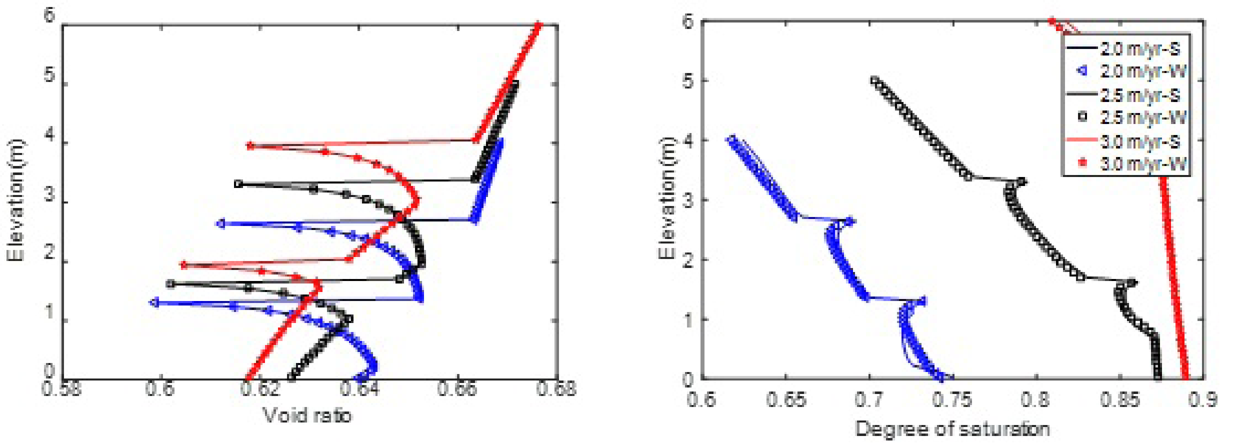


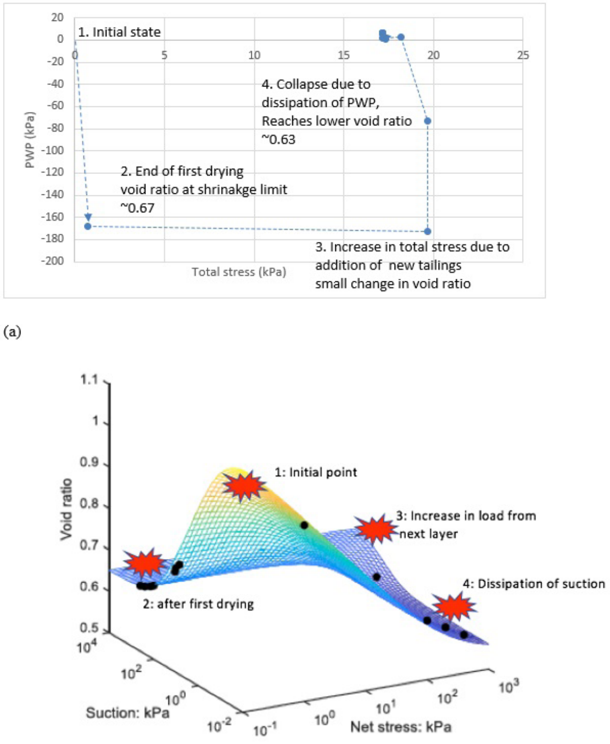
Figure 14. Simulated profiles of degree of saturation and void ratio for different deposition schemes (Rate of deposition, deposition at beginning of summer or winter) (modified from Qi, 2017).

and different deposition times, either beginning of summer or beginning of winter. Regardless of timing of deposition, as in the measured water contents, consolidation dominates the early behaviour, the same water content being achieved in the fresh layer regardless of the season. In the tailings are deposited at the beginning of summer, then the contribution to dewatering by evaporation begins to reduce the water content and void ratio of tailings, while for winter deposition this effect is delayed until to the start of summer. Both methods of deposition, however, end up at the same state at the end of a year.

Figure 14 shows the profiles of degree of saturation and void ratio at the end of three years for all deposition schemes. The range of void ratios is relatively small (0.60 to 0.66) for all deposition scenarios, and all have a significant stress history with respect to desiccation. This is largely due to the favourable consolidation properties of the tailings, which means that they consolidate quickly. Due to this reason, a relatively small amount of time is required for evaporation to induce a desiccation effect. Indeed, shear vane strengths at this site measured in the top layer have values in the range of 30 kPa to 60 kPa.

The degree of saturation, however, is much more variable, the highest deposition rate keeps degree of saturations above 0.85, while for the slowest rate the degree of saturation drops below 0.65. Therefore, if a site is susceptible to acid drainage, it is clear that this kind of analysis can suggest optimal deposition rates. In this case, a deposition rate of 3 m per year would be preferred, as the void ratios are still low, and the tailings still experience substantial desiccation and associated strength gain, while keeping the degree of saturation higher. Practically, this could be achieved by limiting the footprint, or depositing cell by cell using internal dykes.

The void ratios are slightly lower at the top of each old layer. This occurs because the i) contributive effects of total stress (increases with depth) and suction (increases with elevation), and ii) for the points at high elevation, high suctions develop with comparatively low total stresses, which is followed by a substantial increase in total stress following deposition of the next layer, followed by a high degree of suction dissipation – these conditions favour collapse. The substantial increase in total stress, followed by a large decrease in suction, allow the tailings to move to the low suction and high stress part of the plastic constitutive surface (that is, close to the 0 suction plane, or saturated behaviour), which is more compressible. An example stress path is shown in Figure 15, for a point near the surface of layer 1 as it is buried by layer 2.



(a)

(b)

Figure 15. Stress path for a point near the surface of layer 1, as layer 2 is deposited: (a) suction and total stress space; (b) overlaid on plastic surface.

4. Summary and opportunities for future research

The goal of this paper was to illustrate the applicability of unsaturated soil mechanics to design or optimization of thickened or filtered tailings impoundments. To summarize, desiccation is the key parameter that affects the strength of the tailings through stress history effects. These effects manifest in some tailings in terms of increased dilatancy in element testing. The most common negative impact is desaturation and the associated increased risk of acid generation in susceptible tailings. It was shown that consolidation analysis incorporating elasto-plastic unsaturated behaviour can replicate the essential phenomena in multi-layer deposition. Finally, one such analysis was applied to a real field site, showing that useful information of help to operations can come out of such numerical analyses.

The paper has focused on the implications elasto-plastic behaviour in unsaturated soils for multi-layer tailings behaviour, but other aspects are important, for example, the magnitude of the evaporative boundary conditions, the role of cracks, or cold regions applications where freeze-thaw not drying is the driver of desiccation. For evaporation it is generally found from back-analysis of several sites (both thickened, and traditional tailings impoundments in arid climates) (Qi et al., 2017b; Newson & Fahey, 2003; Fujiyasu et al., 2000) and in the large multilayer laboratory tests (Simms et al., 2019), that the effective evaporation can be taken reasonably to be 0.7 x PE (the potential evaporation). This will generally be a larger net flux the predicted by 1-D unsaturated flow models with coupled soil-atmosphere boundary conditions commonly available in may geotechnical software suites, probably because of the influence of cracks (Simms et al., 2019).

Cracking during desiccation in tailings is studied in the above references, but also with respect to modelling the desiccation process (Rodríguez et al., 2007; Yao et al., 2002). In exploring the modelling of tailings in the large drying box types tests, the authors' own experience is that most important influence of cracking, aside from prolonging high rates of evaporation, is the increasing uniform distribution of water content afforded by the effective shortening of the drainage path of water from within the tailing to some exposed surface. This can usually be accounted for, and the distribution of water content within a layer of tailings can be reasonably reproduced, through an upward adjustment of hydraulic conductivity, approximately half an order of magnitude (Qi, 2017). This effect is more dominant in the clayey tailings than hard rock tailings. Cracks are typically filled in or closed under the deposition of successive layers, though there may be some residual effect on the overall strength of a deposit, which is unknown.

Also unknown is the fundamental reason for the particular change in strength behaviour of hard rock tailings when desiccated, that is, an increase in dilatancy. Daliri et al. (2014), looking at SEM pictures obtained on freeze-dried samples of gold tailings, speculated that suction rearranges the internal structure of the tailings matrix, possibly increasing attraction and coating of coarser particles with finer smaller particles, resulting in increased effective particle size, but this is unproven. As stated previously, this effect is quite different than that predicted by elasto-plastic unsaturated models, in term of strength behaviour.

Potentially, similar analysis can be done with respect to desiccation by freeze-thaw effects: similarities between the water-retention curve and soil-freezing characteristic curves are much studied in the literature, including for tailings (Schafer & Beier, 2020). Strengthening tailings and immobilized tailings pore-waters by turning the tailings into "permafrost" is practiced at several mines in Northern Canada: deposition management is based largely on accumulated operation experience. With expected variation in climate expected to increase, application of similar unsaturated soil concepts to deposition in cold regions probably could also assist deposition optimization at these mines.

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Declaration of interest

The author has no conflicts of interest to declare and there is no financial interest to report.

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