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The new expertise required for designing safe tailings storage facilities

Gordon Ward Wilson[1#]

Article

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Abstract

The global mining community has seen a dangerous sequence of failures in tailings dams, beginning with Mount Polley mine, followed by the Samarco, Cadia Valley and Córrego do Feijão mines. This sequence of failures began on August 4, 2014, at the Mount Polley tailings storage facility in British Columbia, Canada. The initial failure in the embankment at the Mount Polley tailings storage facility had substantial impact on the global mining industry. The Independent Expert Engineering Investigation and Review Panel (IEEIRP) tasked with the investigation of the breach in the tailings dam at Mount Polley made major contributions for new guidelines. The incident has given rise to comprehensive recommendations for best available tailings technologies (BAT) based on principles such as the elimination of surface water from impoundments with the promotion of unsaturated conditions in the tailings through drainage provisions. The application of these BAT principles for the surface storage of tailings leads to the use of filtered tailings technology. Filtered tailings technology or “dry stack tailings” can satisfy each of the BAT components when the impoundment is properly designed and constructed. The implementation of the best available technologies for the physical stability (BAT-PS) of tailings impoundments competes directly with the best available technologies for the chemical stability (BAT-CS) of reactive tailings that may produce acid and metalliferous drainage. The new expertise in mine waste management required to achieve both BAT-PS and BAT-CS are discussed in the present paper.

1. Introduction

The global mining community has recently witnessed a series of serious failures in the tailings dams at the Mount Polley, Samarco, Cadia Valley and Córrego do Feijão mines. This sequence of failures began on August 4, 2014, at the Mount Polley tailings storage facility in British Columbia, Canada.

In the case of the Mount Polley failure, approximately 25 million m3 of water and tailings were released into Polley Lake, Hazeltine Creek and Quesnel Lake. The breach occurred suddenly at about 1:00 am and without warning in the perimeter embankment. Fortunately, there was no loss of life. The British Columbia Ministry of Energy and Mines created an Independent Expert Engineering Investigation and Review Panel (IEEIRP) to investigate the breach, and the panel released its report on January 30, 2015. The report can be found at Mount Polley Independent Expert Engineering Investigation and Review Panel (2015).

The Samarco dam disaster in Minas Gerais, Brazil, occurred at about 4:30 pm on November 5, 2015, when the Fundão tailings underwent a catastrophic and fatal liquefaction flow slide, and approximately 44 million m^3 of mine tailings flowed into the Doce River. The cause of the liquefaction flow slide was attributed to lateral extrusion of slimes that had intruded into the sand dam. The full report from the Fundão Tailings Dam Review Panel released August 25, 2016, may be found at Fundão Tailings Dam Review Panel (2016).

The failure at the Cadia Valley Operations in New South Wales, Australia, was not catastrophic but was certainly most significant in attracting the attention of the global mining community. The failure occurred with the wall of the Northern Tailings Storage Facility (NTSF) slumping laterally into the Southern TSF. Prominent cracks within the South face of the NTSF were seen in the morning of March 9, 2018. Significant ground heave was observed at the toe of the NTSF at about 4:00 pm, which prompted the evacuation of the worksite and a small number of downstream residents. A section of the wall

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[#] Corresponding author. E-mail address: ward.wilson@ualberta.ca
[1] University of Alberta, Department of Civil & Environmental Engineering, Edmonton, Alberta, Canada.

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with a width of about 300 m displaced southward by about 170 m. The failure is best described as a mobile slump, and by March 14, 2018, the volume of slump material displaced was calculated to be about 1.3 million m^3. The failure at Cadia Valley Operations had no fatalities. The Independent Technical Review Board released its final report on April 17, 2019, and it can be found at Newcrest (2019).

The failure of Feijão Dam I occurred on January 25, 2019, at approximately 12:28 pm. The fatal failure was a sudden, catastrophic liquefaction flow slide. The failure was recorded on high quality video, and the failure was seen to extend across most of the face of the dam. Collapse of the downstream face of the dam was complete in less than 10 seconds. Approximately 9.7 million m^3 of material that represented about 75% of the tailings contained in the dam was released in less than five minutes. The report of the expert panel on the technical causes of the failure of Feijão Dam I was published on December 12, 2019, and can be found at Feijão Dam I Expert Panel (2019).

All four of these major and prominent failures occurred within a period of less than five years. Moreover, these failures occurred in contemporary tailings dams constructed under good conditions and with no environmental extremes or usual stresses. These failures have generated an unprecedented response in the global mining community. The old paradigm of business as usual has completely evaporated. For example, in Canada, leading entities such as the Canadian Dam Association and Mining Association of Canada, as well as the International Council on Mining and Metals, have published new and comprehensive guidelines. The author believes that the Mount Polley IEEIRP provided a major contribution for many of these new guidelines in that a component of the mandate given to the IEEIRP was to recommend best available tailings technologies to improve dam safety. These will be discussed in the following section of this paper.

2. Recommendations arising from the Mount Polley failure

According to the Mount Polley IEEIRP report, the failure on August 4, 2014, occurred as a slump in a short section of approximately 250 m within the 40 m to 50 m high perimeter embankment at the Mount Polley tailings storage facility. The slump was cause by a sudden foundation failure in the embankment. The crest of the embankment dropped approximately 2 m, which allowed the high water level in the pond to overtop the crest of the dam and cause a large breach to form and down cut by rapid erosion. The were no eye witnesses who observed the failure at 1:00 am. The foundation failure formed in the glaciolacustrine unit at the base of the slide, which failed in undrained loading. A comprehensive three-dimensional numerical modelling program showed that the collapse occurred with the strain-weakening of a thin shear band in the glaciolacustrine unit at the base of the slide (Zabolotnii, 2020). The failure mechanism articulated by Zabolotnii (2020) was not recognized during the original design of the embankment.

As noted in Wilson et al. (2017), as a result of the comprehensive enquiry completed at Mount Polley, the IEEIRP recommended the implementation of best available tailings technologies (BAT). In terms of risk-based dam safety practice, “the panel does not accept the concept of a tolerable failure rate for tailings dams” and advocated the implementation of the best available tailings technology based on the BAT principles outlined as follows:

1. eliminate surface water from the impoundment,
2. promote unsaturated conditions in the tailings with drainage provisions, and
3. achieve dilatant conditions throughout the tailings deposit by compaction.

The application of these BAT principles for the surface storage of tailings leads to the use of filtered tailings technology. Filtered tailings technology or “dry stack tailings” can satisfy each of the BAT components when the impoundment is properly designed and constructed. The panel refers to the Greens Creek mine in Alaska, USA, shown in Figure 1, as an example of where “dry stack tailings” has been successfully implemented. It is important to note that the regional climate regime is paramount in the design of any tailings impoundment, but in this case, the Greens Creek mine was selected by the panel due to its proximity to the province of British Columbia.

The application of the best available technologies for the physical stability (BAT-PS) of tailings impoundments requires new knowledge and new expertise. This new knowledge and expertise must overcome the inherent or embedded ignorance (Morgenstern 2020) that exists in tailings management. The term ignorance carries a negative connotation and that is not the intent of its use here. The definition of ignorance by the Merriam-Webster is simply lack of knowledge, education, awareness, and it is within this context that the term is used herein. Two examples of problems associated with embedded ignorance are illustrated here to help articulate the challenges for the design, operation and closure of many

Figure 1. Filtered dry stack tailings at Greens Creek mine, Alaska (Wilson & Robertson 2015).

tailings storage facilities generally found in the base and precious metal industries.

3. Challenges with physical and chemical stability

Implementation of BAT principles creates serious challenges with current best practice. The principle of physical stability (BAT-PS) strongly competes with the best available technologies for the chemical stability (BAT-CS) of reactive tailings. The application of BAT-PS principles is to drain and dry the tailings profile, which results in increased oxidation potential for acid rock drainage and metal leaching (ARD/ML) in reactive tailings. In contrast, the maintenance of fully saturated conditions in a tailings profile along with the use of water covers for the closure of potentially acid generating waste has been considered best practice to prevent or limit acid generation in several jurisdictions. Figure 2 illustrates the preferred solution of using water covers for the prevention and control of ARD. Water covers are routinely employed as a preferred strategy for the long-term closure of reactive tailings worldwide as outlined by the global acid rock drainage (GARD) guide (INAP, 2014). However, the containment of a permanent water pond on a tailings dam for closure creates an everlasting geo-hazard that requires perpetual monitoring and maintenance.

The examples shown on the left side of Figure 2 are ideal closure configurations for sub-aqueous disposal, since the tailings and water cover do not require above ground containment structures and both chemical and physical stability (i.e. BAT-CS and BAT-PS) are completely satisfied. On the contrary, with the examples shown on the right side of Figure 2, while satisfying chemical stability (BAT-CS), the condition for long-term physical stability (BAT-PS) is most certainly not guaranteed. The required confinement of a water cover above the surrounding topography is a permanent geo-hazard that must be maintained into perpetuity. Tailings dams that require regular inspections and maintenance eliminate the possibility of walk away at closure, impose complexities with monitoring and increase long-term risk. In fact, strict application of a risk-based approach dictates the probability of failure over longer time scales is arguably approaching 100%.

4. Challenges associated with unsaturated soil mechanics

The use of filtered tailings at Green Creek eliminates the surface water pond from the waste facility, promotes unsaturated conditions in the tailings with drainage provisions and achieves dilatant conditions throughout the tailings deposit by the use of mechanical compaction. While these characteristics promote BAT-PS, the de-watering of tailings to produce an acceptable filtered product can be expensive, especially in the case of pressure filtration. In addition, the implementation of filtering tailings at sites with high tonnages is also very challenging.

The primary issue with dry stack tailings impoundments is that they form positive topographic structures that rise above the surrounding terrain and water tables. Consequently, they form unsaturated mined earth structures, as a result of drainage to the foundation and water losses to the atmosphere due to evaporative drying. Figure 3 shows the surface of a dewatered tailings deposit with a layer of unoxidized tailings overlying oxidized tailings. The tailings profile is unsaturated, and the lower layer of reactive tailings has oxidized with the ingress of atmospheric oxygen. The upper unoxidized layer of fresh thickened tailings, deposited after the underlying tailings were already oxidized, can be expected to oxidize with time in the same way as the previous lower lift of acid-forming tailings. In summary, the BAT-PS principles for the elimination of surface water from the impoundment and the promotion of unsaturated conditions in the tailings can be seen to directly contradict the general principles laid

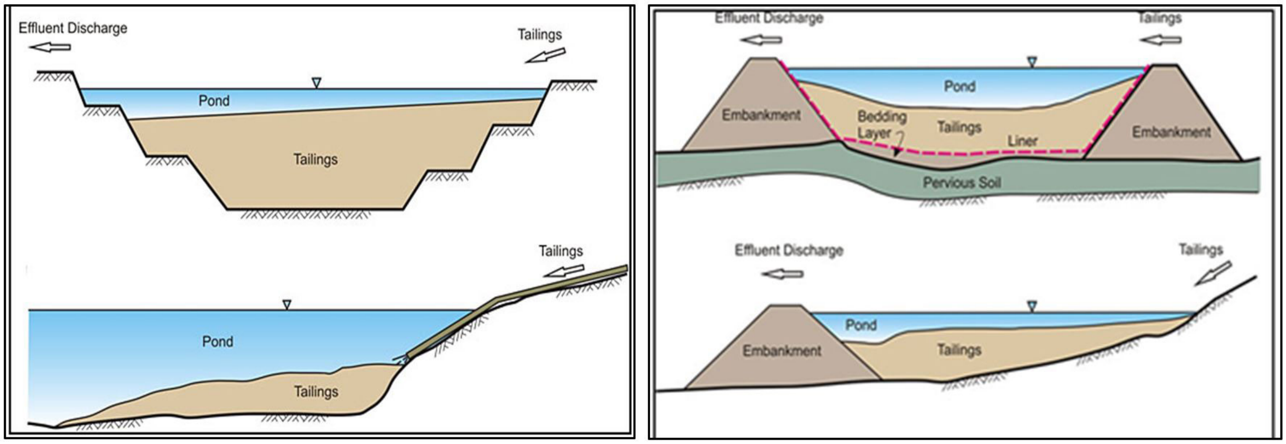


Figure 2. Sub-aqueous disposal for chemical stability (modified from INAP, 2014).

Figure 3. Thickened tailings with unoxidized layer overlying oxidized tailings.

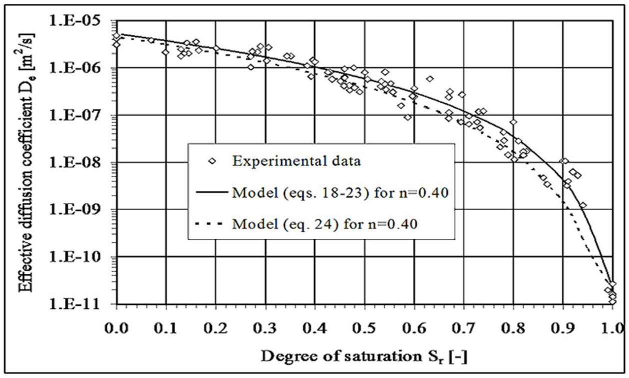


Figure 4. Oxygen diffusion coefficient versus degree of saturation (Aubertin, 2005).

out in the GARD guide (INAP, 2014) for the prevention of ARD and metalliferous drainage or BAT-CS. Mine waste professionals are left with a serious and competing conflict in their design criteria.

A key component for the design of de-watered tailings deposits is the degree of water saturation within the tailings profile. Tailings profiles with water saturation levels greater than 85% are considered resistant to oxygen diffusion and subsequent ARD. Figure 4 shows the effective diffusion coefficient of oxygen (De) as a function of the degree of saturation (S). The figure shows that De decreases by several orders of magnitude as the degree of saturation increases from zero to 100%. Furthermore, the decrease in De becomes most significant in the range of 85% saturation; thus, maintaining S at 85% or greater has become a target or criteria in the design of mitigative measures to control or prevent ARD in potentially acid forming (PAF) mine waste materials.

Satisfying the condition for physical stability (BAT-PS) in tailings is controlled in part by the degree of saturation. Saturated contractive tailings are the most susceptible to liquefaction, while dry tailings are generally non-liquefiable. While saturated tailings are most resistant to the diffusion of oxygen that drives ARD (BAT-CS), saturated tailings are the least desirable in terms of physical stability (BAT-PS). However, it is generally accepted that tailings profiles with water saturation levels less than 85% are considered resistant to liquefaction. A degree of water saturation equal to 85% marks a key design target or metric for both BAT-CS and BAT-PS, albeit in an inverted or overturned fashion. In summary, successful implementation of the BAT principles for both PS and CS demands insight and knowledge of the field of unsaturated soil mechanics.

A degree of water saturation equal to 85% appears to be a key target for achieving both chemical and physical stability in reactive tailings (Aubertin, 2005). Figure 5 shows a typical soil–water characteristic curve (SWCC) for tailings The SWCC controls water saturation as a function of matric suction. Generally, a value of S = 85% (based on the tangent technique) corresponds to a very important point on the SWCC known as the air entry value (AEV). The AEV corresponds to the value of matric suction at which the largest pores drain and air enters the matrix of the tailings (i.e. bubbles). It is important to note that while air bubbles exist in the matrix, the air phase is not continuous. This explains why the diffusion coefficient for oxygen De decreases dramatically at S = 85%, corresponding to the AEV. In a similar way, the development of air bubbles at the AEV reduces the potential for liquefaction since excess porewater pressures can be dissipated with the flow of water to the air-filled voids in the largest pores of the tailings matrix. In summary, the AEV corresponds to an optimum point on the SWCC for the simultaneous minimization of both oxygen diffusion in reactive tailings and porewater pressure generation in liquefiable tailings.

Controlling the saturation profile demands the coupling of the net infiltration rate with hydraulic properties of the tailings that in turn are controlled by the SWCC, AEV and unsaturated permeability (ksat) function of the tailings (Bussière & Guittonny-Larchevêque, 2021). In general, under downward drainage with a hydraulic gradient of unity, the long-term steady state net percolation rate (shown in Figure 6) entering the surface of the tailings profile must be equal to the unsaturated hydraulic conductivity (as defined by the SWCC and AEV) of the tailings. Furthermore, the infiltration rate is determined on the basis of coupling hydraulic properties of the surface of the tailings or cover system with the microclimatic conditions. In summary, the final cover

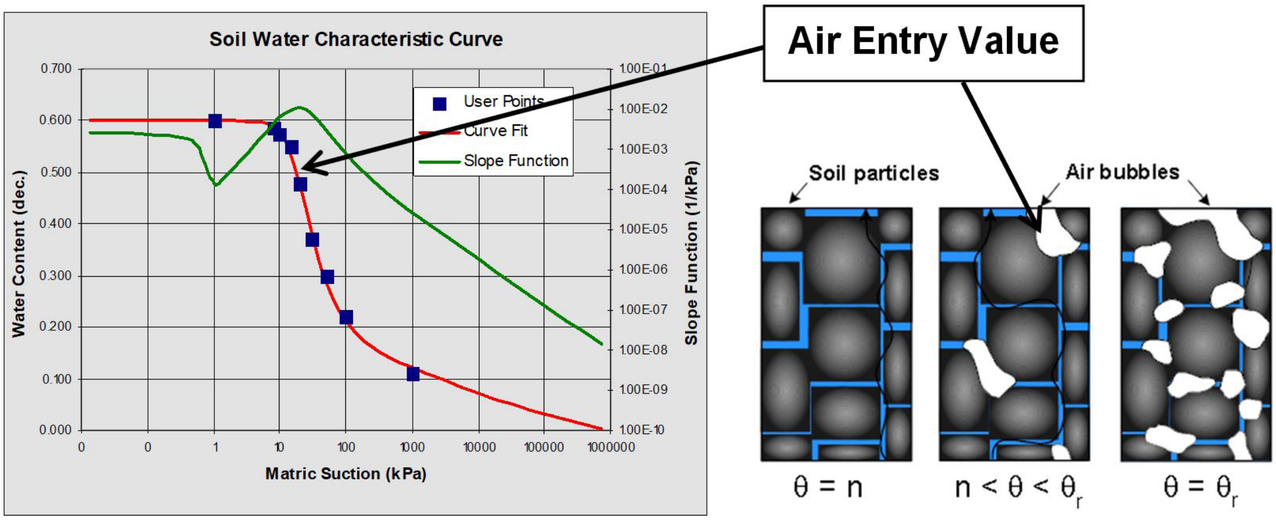


Figure 5. Typical soil-water characteristic curve for tailings.

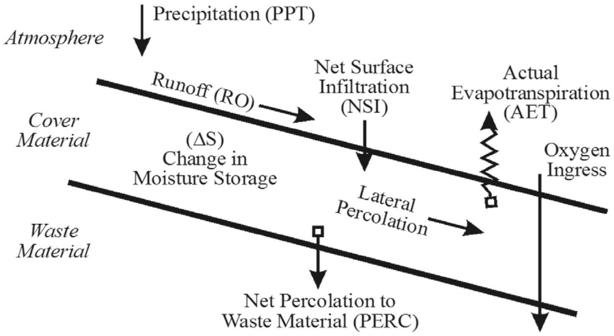


Figure 6. Components of the surface water budget and net percolation for tailings. Source: Mine Environment Neutral Drainage (MEND) Program (2017).

system design for closure must provide infiltrative fluxes that optimize unsaturated flow conditions in the tailings.

5. Challenges for designing new tailings management facilities

As stated above in Section 2, the IEEEIRP advocated the implementation of the best available tailings technologies based on BAT principles. Furthermore, the IEEIRP declared that the application of these BAT principles for the surface storage of tailings leads to the use of filtered tailings technology. Filtered tailings technology or "dry stack tailings" can satisfy each of the BAT components when the impoundment is properly designed and constructed. Designing dry stack tailings systems that satisfy both BAT-CS and BAT-PS will require rigorous application of the principles and theory for unsaturated soil mechanics outlined above.

The IEEIRP referred to the Greens Creek mine shown in Figure 1 as an example of where "dry stack tailings" has been successfully implemented. Numerous other dry stack facilities have been constructed or are under construction, or are being planned, as mentioned in the MEND (Mine Environment Neutral Drainage (MEND) Program, 2017) report. Some of the new dry stack facilities currently being considered are at mine sites with productions in excess of 100,000 tonnes per day. Figure 7 below shows an example of the large dry stack system proposed at Rosemont mine in Arizona, USA. The design, analysis, instrumentation, monitoring and assessment of dry stack tailings systems is radically different when compared to conventional tailings dams.

Dry stack tailings systems, by definition are positive topographic tailings deposits that are intended to remain permanently unsaturated, and therefore, special or nonconventional theory (i.e. unsaturated soil theory), methods of analysis, laboratory test procedures and field instrumentation are required. To illustrate the difference, the seepage analysis required for a conventional slurry impoundment with a water pond compared with that for a dry stack tailings system can be considered. The principal upper boundary condition for the surface of the conventional tailings impoundment is a head boundary condition that is established by the elevation of the pond. However, no such boundary condition exists for a dry stack tailings deposit. The surface boundary condition for seepage in a dry stack tailings deposit is a flux boundary condition established on the basis of coupled soil–atmosphere modelling determined by the hydraulic properties of the surface of the tailings cover together with microclimatic and atmospheric forcing conditions.

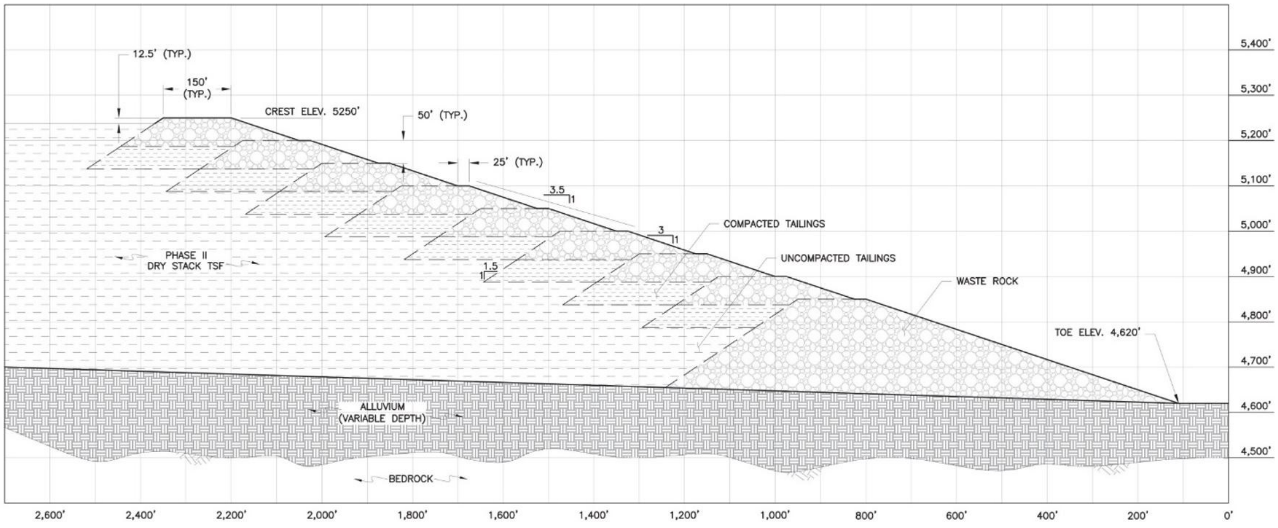


Figure 7. Rosemont dry stack tailings (AMEC Earth and Environmental, 2009).

The prediction and measurement of actual evaporation is perhaps the most difficult variable to quantify and requires highly advanced instrumentation such as the eddy covariance (ECV) apparatus shown in Figure 8. Inverse (or back) analyses are also often used and require the installation of water content probes in the tailings profile. Nevertheless, evaporation is routinely determined on the basis of pan evaporation measurements or methods of analysis based on micro-meteorological measurements for solar or net radiation, temperature, relative humidity and wind speed. However, these methods provide estimates solely for potential evaporation, which can be a source of great error since actual rates of evaporation are much less than potential values; thus, the simple water balance equation becomes highly indeterminate.

In addition to the difficulty in defining appropriate boundary conditions for modelling unsaturated flow in dry stack tailings, equally difficult challenges arise for the in-situ measurement of porewater pressures and associated hydraulic heads. In the case of conventional saturated slurry tailings deposits, porewater pressures and hydraulic heads are measured with conventional piezometers such as the Casagrande piezometer and/or vibrating wire piezometers. However, such instruments are virtually useless in dry stack tailings unless saturated conditions are forming, such as at the base of a stack. Conventional piezometers will still be required in dry stack systems but only to check if saturation is developing that might be causing dangerous conditions for instability.

Proper instrumentation for the monitoring of porewater conditions in unsaturated dry stack tailings will require the installation of instruments to measure matric suction. Figure 9 illustrates an example of an instrument for the measurement of matric suction as low as 1 kpa known as the Fredlund thermal conductivity sensor. Such instruments will need to be installed within the profiles of dry stack tailings, similar to the nested profiles commonly used for conventional piezometers.

Figure 8. Eddy covariance instrumentation (ECV) on a tailings surface.

The determination of soil property functions for saturated/unsaturated flow in dry stack tailings is perhaps the most important component of seepage modelling for dry stack systems. Seepage modelling in an unsaturated system is controlled by the SWCC and the associated permeability function for the tailings as shown in Figure 5. However, the SWCC, which is a function of the particle size distribution, is also strongly influenced by total stress and density as can be seen in Figure 10. The key components in the design of a dry

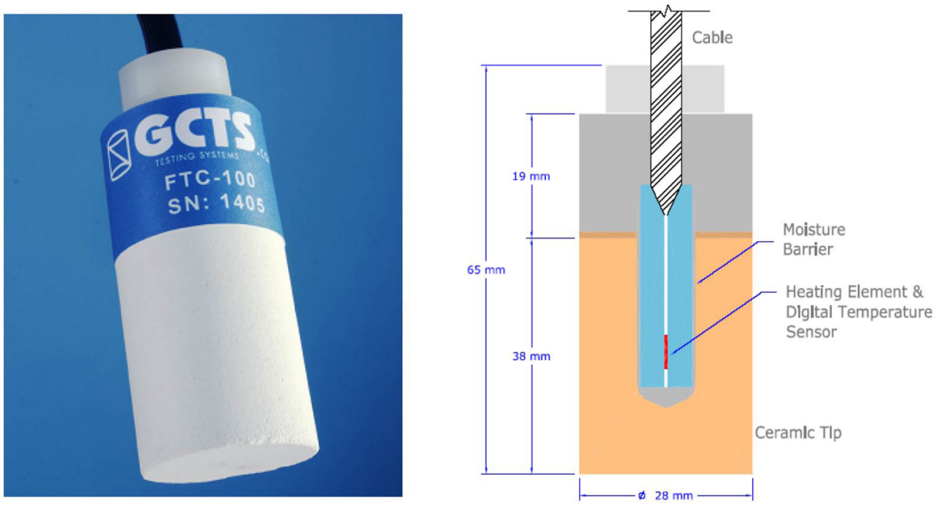
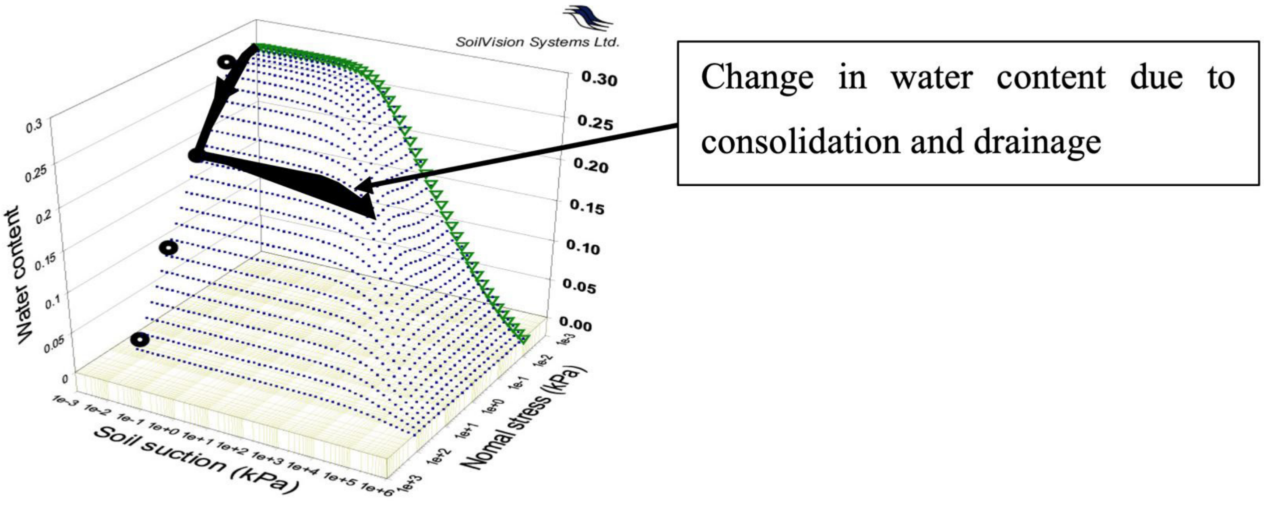


Figure 9. Fredlund thermal conductivity sensor (FTC-100). Source: GCTS (2021).



Change in water content due to consolidation and drainage

Figure 10. An example constitutive surface for a saturated/unsaturated tailings profile, showing a potential stress path for loading (after Fredlund, 2000).

stack system are to achieve physical stability (BAT-PS) and dilatant conditions throughout the tailings deposit by compaction and/or in-situ stress. The determination and application of the constitutive surfaces for dry stack tailings, such as the example presented in Figure 10, will be paramount in terms of coupling the seepage analysis with the stress analysis.

6. Summary and conclusions

The failure in the embankment at the Mount Polley tailings storage facility in British Columbia, Canada has had substantial impact on the global mining industry. The Independent Expert Engineering Investigation and Review Panel (IEEIRP) for the breach in the tailings dam at Mount Polley made major contributions to new guidelines. The incident has given rise to comprehensive recommendations for the best available tailings technologies (BAT) based on principles such as the elimination of surface water from impoundments with the promotion of unsaturated conditions in the tailings through drainage provisions. The application of these BAT principles for the surface storage of tailings leads to the use of filtered tailings technology. Filtered tailings technology or “dry stack tailings” can satisfy each of the BAT components when the impoundments are properly designed and constructed.

The implementation of the best available technologies for the physical stability (BAT-PS) of tailings impoundments competes directly with the best available technologies for the chemical stability (BAT-CS) of reactive tailings that may produce acid and metalliferous drainage. Mine waste management methods directed at achieving both BAT-CS and BAT-PS were discussed in the present paper. The application of unsaturated soil theory and special methods of analysis, laboratory testing and field instrumentation will be required for designing new tailings management facilities.

Declaration of interest

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

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