Water in Tailings: a review of 20 years of post-closure tailings performance

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Abstract

The industry has closed and reclaimed a number of tailings storage facilities, meeting the industry good practice at the time the work was carried out. Subsequent events in the mining world causes us all to rethink those criteria and now we see that there are significant subtleties that might escape the caretaker of a closed facility. Many of these are water-related, and this paper serves to point out some things to consider as we update our criteria, modify our practices and upgrade these facilities in the future.

The fact that these facilities have been in place for many years is encouraging, and one is inclined to take comfort that nothing has gone wrong. But our conceptualization of how tailings storage facilities perform in the long term has been called into question over the past ten years or so. Today's approach is to be more conservative given that, despite all the improvements in test methods, analyses, etc, dams are still failing. We should perhaps take less comfort in chance and pay more attention to the consequence of a failure should it occur. When one adopts that approach, the elimination of critical failure modes is an imperative, as is thinking though what would happen should the future not manifest as we predict it to.

The paper discusses: seepage and groundwater impacts; freeboard and flooding; and draindown and strength gain.

Introduction

The observations of the authors are based on the review of a number of tailings storage facilities in the past 5 years leading up to and in response to the global industry standard on tailings management (GISTM), now being adopted by a majority of mining companies and endorsed by the risk management and finance community. The key finding of note here is the critical role water plays in the performance of the materials themselves and the structure as a whole.

Conventional tailings disposal involves decantation of a slurry in a large reservoir, recovering the water for re-use and settling the solids into a stable mass. Some facilities were constructed in valleys, adopting geometries suitable for water dams and impounding runoff from areas upstream of the dam.

Without fail, the early facilities discharged impacted water to the aquifer and in some cases to surface waters downstream. The volume of water contributed to the aquifer over the operating life of the facility dwarfed the seepage since operations ceased, making source control now a somewhat token gesture unless the tailings have more recently become more reactive and seep water quality has deteriorated significantly.

A second topic of interest to the design engineer is that of the design basis: how have the set of assumptions made by the designer stood the test of time? We have the benefit of far larger bodies of climate data so can refine our estimate of the design storm, for example. At the same time our collective appetite for risk is lower and some facilities, considered state-of-the art when constructed and later decommissioned, do not meet the standards of today.

In the case of dams built using the upstream method, the tailing material itself formed the outer shell of the facility, resulting in a heterogeneous mass. Uncertainty about the material properties in key structural zones has causes many owners to investigate and re-evaluate the dams. One of the more common findings of these investigations of older facilities is that while the assumption about draindown, consolidation and strength gain are generally valid, in certain key zones the fine-grained materials may yet to retain enough moisture to behave poorly under seismic loads.

The three broad themes are somewhat related, as will be apparent from the following discussion. The work of the tailings engineer requires an understanding of all these topics: how the materials and water interact and how the resulting landform will behave under the stresses nature imposes on it. This is interesting!

Chemistry and Time

The most significant shift in thinking over the past 20 years has been in how we define our timeframe of concern. A common approach was to externalize the potential future impacts because the rules and practices at the time allowed us to do that. We put a limit to our evaluation of what are essentially geologic processes occurring in a geologic timescale, framing the problems in some thing we could understand: our lifetime. Now we clearly see that the facilities in our care will outlive us and we should think in terms of the lifetime of the tailings storage facility.

The system we interrupted, to extract the mineral wealth, will recover to some, new, equilibrium. How fast the system re-equilibrates depends upon how much fuel is in the fire, so to speak, and water is the great diluter and flusher of the products of any chemical reactions. In many cases interventions have been put in place to limit the rate of reaction (covers), limit the flow of water through the reactive material (shaping and covering) and to intercept impacted water to limit impacts to receptors downstream. Now we have evidence as to the effectiveness of these interventions (and they are effective) but have learned that in some cases they may be required permanently, rather than for the finite time we anticipated. The upshot is that "closure" is not a thing we do once, but a very long post-mining period. Water being the primary vehicle for mobilizing minerals through our environment, managing the influx, reaction with, and egress of water is of primary concern to mining companies.

Groundwater

Environmental and demographic shifts cause us to see the value of groundwater differently now than we did in the past, and miners are held to new standards with respect to quality and availability. The right to contaminate is being challenged, and levels of contamination previously considered innocuous may no longer be acceptable.

Tailings Chemistry and Water

The chemistry of tailings water is first a function of the process used to extract metals and later a function of the mineralogy of the material itself. When the tailings is first deposited (historically always as a slurry) the water chemistry is dominated by the residue of whatever chemical reactions were employed to separate the metal values from the residual tailings. Later, as that process water drains and is further flushed from the system, the chemical signature shifts towards a function of the mineralogy of the tailings material itself, how available those minerals are to react and how fast they react. Water plays a key role as the flushing agent. When the flow is great enough that the tailings approaches saturation, water acts as an inhibitor of chemical reaction – this because most mine drainage needs oxygen.

In Arid Regions

Where water is scarce (in very dry regions) the reactivity of tailings may be less important as the contribution of mine drainage to the aquifer is small after deposition ceases. However, aquifers in arid regions may be quite sensitive to mine water impacts and the groundwater resource is prized because it is a scarce resource. So it is not correct to say that water is less of an issue in arid regions.

A significant volume of water with the process-water fingerprint may be (or may have been) discharged to the environment during operation of the facility, although more modern installations include measures to limit seepage losses and recover seep water for re-use. This plume of impacted water, once sent on its way, cannot be mitigated though source control, the principal source having been shut off when deposition of tailings ceased. The impacts of this body of process water can be seen for many years as the aquifer accommodates the additional water and chemical mass, and mask the impacts of the much smaller flow of mine drainage that follows.

When the tailings drain and (over a long period) the process water is flushed from the system, air (oxygen) will enter the pore spaces and react with the minerals in the tailings. Although the material may be highly reactive and the resulting drainage of unacceptable quality this can often be managed by limiting the ingress of water so that the products of the reaction are not flushed into the groundwater at an unacceptable rate.

In High Rainfall Regions

Where there is an adequate supply of water it has sometimes been convenient to use a body of water as a cover for tailings, either by depositing tailings in a natural lake or placing tailings in a reservoir behind a dam designed for the purpose. In such a case there will be a large volume of water in contact with the tailings, but very little oxygen will be available to fuel any mine drainage generating reactions. These facilities have performed well and are an effective way to limit the impact of reactive tailings. The desired performance depends then on the safety of the dam and the management of the water cover. Together these constitute a very long term obligation on the part of the owner to maintain the dam, procure the water and manage the quality of the excess surface water passing through the system.

The common case

Reactivity is limited when water is abundant enough to cut off access to oxygen, resulting in reasonable water quality. Reactivity is favored when water is scarce and oxygen can enter the pore spaces, but the contribution to the environment may be small. The challenging situations arise when there is a periodic pulse of water to flush the products of oxidation into groundwater. Most installations fall somewhere between the extremes and encounter this challenge, with the potential impacts of the smaller periodic flow masked initially by the much greater flow of process-related water. In any event it can be many years before a system achieves some steady state and the effectiveness of the controls can be validated. During that time it is quite possible that the goal posts with respect to groundwater protection move, making this an even more challenging issue.

Surface Water

Modern tailings facilities tend to be built so that the upstream catchment area is small and the risk of inundation by a storm limited. That was not always the case in the past. The cost of initial construction is influenced greatly by the size of the dam, and the effort to subsequently raise the dam is a function of the crest length. Placing tailings in an existing valley makes for an efficient storage facility, but potentially with a greater risk of inundation.

Several factors influence our current thinking with respect to surface water management. A quick review of tailings dam failures illustrates that where water was impounded the flow was greater and went further. From a dam safety perspective then, unless the facility is designed to do so it is now considered good practice to avoid storing water on the facility. As discussed above, unless the water cover is permanent it is not advantageous chemically to have fluctuating water levels (in the case of tailings varying extent of the pool) as alternate wetting and drying can lead to poor quality seepage to groundwater. A third consideration is how much water one needs to store to avoid overtopping the dam in an unacceptable way, and our understanding of the design flood has changed.

The Design Storm

Flood hydrology used to be based on a set of real data manipulated using statistical methods to arrive at an estimate of rainfall duration, intensity and quantity. The techniques are not flawed, but we continue to be frustrated by new data that tends to challenge how we predicted things would be. The big manifestation of this is transient nature of the weather patterns we based our predictions on - tomorrows weather may not follow yesterdays' pattern. The only reliable assumption is that we will likely be proven wrong, in the very long term.

The GISTM requires that we manage the tailings facilities, protecting them from the effects of earthquakes, floods and general weathering. In days gone past local regulations were considered adequate and a 1:100yr or 1:200yr storm (beyond our lifetime) was considered adequate. Now that we have accepted that these facilities will need to remain intact, to be protective of the environment, for much longer, and that a 1:100 yr event can actually occur *in our lifetime*, it is customary to consider the 1:10,000 yr event or the probable maximum flood. Calculating the 1:10,000 yr event statistically is a challenge and it is becoming more common to estimate the probable maximum runoff using temperature and humidity and precipitation data compiled globally, making some allowance or the climate trends we are observing.

Runoff

The impact of a precipitation event is a function of the rate at which runoff arrived at the impoundment and either needs to be contained or conveyed through the facility and over the spillway. In colder climates the greatest runoff is experienced when a rain event melts the accumulated snow and the combined mass of water arrives together. As our climate warms we are likely to experience more rain-on-snow events during the spring thaw.

Another climate- or environment-related factor is fire. Storms following shortly after a large burn in the catchment area can result in significantly greater runoff and runoff intensity than anticipated. Under these post-fire conditions the sediment load might be significantly greater than originally considered, causing the hydraulic performance to vary from that anticipated in the design.

The Design Flood

New approaches and guidance (CDA, for example) as to how the design storms are estimated have led to the reevaluation of design of freeboard and spillway capacity. Hydrologists today estimate the inflow design Flood (IDF) and Environmental Design Flood (EDF) by determining the combination of duration and frequency, including rain on snowmelt events that produce the greatest volumes, peak flows and resulting hydrographs. The storm hydrograph is different today as it considers climate change and the available site-specific climate data gathered since closure. We are now faced with the question whether we upgrade spillways and raise dams to accommodate very low likelihood events, when facilities were closed in good faith to the criteria of the day. Considering these facilities may exist to perpetuity, one can expect that each generation of engineers will be faced with this question, for marginal reduction in risk.

Passing a greater Inflow design Flood (IDF) may require a larger spillway or additional backwater capacity. This is influenced less by the total volume of the flood and more by the peak intensity and how fast the flood can pass through the impoundment and over the spillway. This can be limited by the spillway capacity, volume of the impoundment and in some cases the capacity of the receiving waters downstream.

The Environmental Design Flood (EDF), which is the quantity of water to be stored without treatment (below the spillway invert), is also affected by changes in guidance and approach. EDF storage is required in tailings facilities that have water covers, either for ARD control or radiation protection, and is more common in cooler climates. A greater EDF required additional storage capacity. Where the normal operating level cannot be lowered to make room for larger EDF storage due to other constraints (I.e, such as exposing tailings), facility upgrades such as a raised spillway and crest might be required.

Soil Mechanics and Water

Water serves as the great lubricant and causes the tailings engineer great concern. In the past it was common practice (and in many cases it remains the practice) to construct paddock dams using the tailings material itself and incrementally raise the tailings storage facility. Classical tailings design presumed that the materials would drain and consolidate after placement. The continued draining and consolidation when operations cease has been relied on to explain how the longer-term design parameters and factors of safety will be accommodated by the structure as it continues to gain strength. The following section relates principally to facilities *built from tailings*, and classic water-retaining structures are a different case.

Hydraulic Placement of Tailings

Larger (heavier) particles require more energy to be moved, so tend to settle out first when tailings are discharged at the edge of the impoundment. The finer (smaller, lighter) particles will remain in suspension until the water stills in a pond. Constructing an embankment using hydraulically deposited tailings presumes that the fine and light particles have been carried further from the discharge point, beyond the zone where the strength of the materials influences the slope stability.

Quality Control

A tailings storage facility might be constructed over many years, working continuously, day and night, through the range of seasons. The operator must accommodate floods, droughts, stoppages and changes in material properties as different zones in the ore body are exploited. Today we have video surveillance and satellite-linked instrumentation to aid us, but in the case of some of the older facilities there is a paucity of records indicating how material was placed and what the properties are. What we have found through subsurface investigation and review of available records is that the pond was not always where it was meant to be, was often larger than planned, and the fine material is not always confined to the zones where is would have little influence in slope stability.

Draining, Consolidation and Strength

Materials placed hydraulically when allowed to drain will experience consolidation and settlement under their own weight and the weight of the materials above them. It is important that they drain so they are not buoyed by the water around them and can come into full contact with the adjoining particles. In a clean sand this is a very effective way of placing and compacting materials so they have a reliable strength.

Fine-grained materials have low permeability and a large surface area so tend to let go of entrained water very slowly. At depth there is no evaporation and the capillary forces tend to sustain a state of near saturation: A soil sample will indicate moisture contents near saturation but a Casagrande-type well will yield no free water. This is not bad in and of itself, but is inconvenient when this condition is encountered in a zone where this sort of material was not anticipated.

Liquefaction

Our understanding of soil liquefaction continues to expand through laboratory testing and, unfortunately, back-analysis of actual slope failures. Suffice to say for the purposes of this paper that liquefaction can occur not only when a material is submerged (saturated). Under the right conditions it can occur in soils that are almost saturated - that is, when there is enough water in the pore space to interfere with the stress-strain relationship under rapid loading.

Flux and Recharge of fine layers

In dry regions it is common to deploy thin covers that encourage evapo-transpiration. These are highly effective and, do prevent most water from percolating into the tailings most of the time. This is generally adequate for the purposes of protecting groundwater, as discussed previously. At issue is how much water can be allowed to pass into the system and pass through the fine layers without leading to local almost-saturation in zones key to the stability of the structure?

Excavations at considerable depth in tailings placed twenty-plus years ago indicate that the fine materials tend to sustain moisture contents close enough to the point of saturation to be of concern to the geotechnical engineer. Whether the subsurface condition might have been different has the surface been shaped or treated differently in an effort to limit infiltration remains a topic for further study.

The challenge posed by these fine layers then is that they complicate the argument made for consolidation and strength gain. When the fine layers do not drain fast enough they might still be susceptible to liquefaction (unless subject to adequate overburden pressure) and strength loss. The question is whether, with the right surface treatment and given enough time, draining and consolidation might *eventually* result in conditions that are not a concern?

Conclusion

The brief analysis above indicates the key role that water plays in the performance of tailings and how some rather simple measures might benefit the long-term performance of a storage facility. It warrants repeating: the tailings engineer (and the mine closure practitioner) must work with the circumstance at the site in question, as not all the potentially advantageous approaches are applicable everywhere. It is evident though that all approaches should be considered as they serve as counterpoints to each other. If, for example, a wet cover seems attractive because limiting the exposure to oxygen would be beneficial, but the climatic setting is not conducive to such a cover, the designer can explore alternative ways of achieving a similar effect. Water will serve as both friend and foe depending upon the particular element of the tailings facility being considered, and it is crucial that designers adopt a multi-disciplinary approach and have a keen understanding of the role water plays in the whole system.

The soil mechanics of mine tailings is being extensively studied presently and in the coming years we will likely see a valuable body of work arising from that effort. In the meantime we must use our observations of past performance to empirically adopt suitably safe designs in the structures we are building today.

The question of very long-term performance is key when the mining industry is to meet our commitments to the community. It is becoming clear that the climate is far more variable than we considered likely when many of these tailings management facilities were originally designed and built. Additionally, we continue to adapt our range of concerns as we gain an appreciation for hazards and learn more. The variability in conditions (and, perhaps, the future material properties) requires us to become experts in risk-based decision making and to take the adaptive management approach. It is imperative that we continue to monitor the behaviour of the structures in our care and share what we learn so that our designs and modes of operation are adequately informed.

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