International tailings failures and best available technology

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ABSTRACT

Recent events in western Canada within the last year have focused our attention as geotechnical engineers within the mining industry:

- A plunging oil price against a backdrop of already depressed mining commodity prices has applied pressure to the process of tailings and geotechnical design.

- We witnessed one of the largest tailings failures worldwide ever (in terms of volume), after which the Expert Panel who were appointed to investigate the failure concluded that the "dominant contribution to the failure resides in the design."

This is perhaps an important time for us to pause and reflect on our work in tailings engineering, with a somewhat broader international perspective, and to ponder a few questions:

1. What were some of the salient tailings failures around the world over the past 50 years?

2. What are the leading mechanisms of failure for tailings facilities?

3. In response to the call for the adoption of Best Available Technology, how do we define Best Available Technology (BAT) for the tailings industry?

4. What foundational principles might point us to BAT?

5. What tailings technologies should we be considering more closely, and how could these technologies be applied to reduce our exposure to risk?

6. What changes could be made to introduce and advance best available technology in all aspects of tailings engineering?

In this paper the authors offer their insights in reply to the questions posed above.

Keywords: Risk, geotechnical, mechanisms, principles, design, regulation

1 INTRODUCTION

For those of us who have worked in the tailings industry for some time, it is disturbing to note history repeating itself. Catastrophic flow failures appear to follow one another around the world. Every year, there is a tailings failure somewhere. Every decade, there is loss of life. The situation just repeats itself - the community outrage, the environmental devastation, the media outcry, the tumbling of share prices, the legal investigations, the tightening of regulations, the publishing of technical papers and the distillation of the likely causes. Until a generation has passed. Then it all happens once again.

Are we missing something? Are we condemned to merely watch history repeat itself, despite our best efforts as engineers? Why does our increasing knowledge, wealth of experience and advancing technology not equip us better to avoid these catastrophes? Is there a pattern? Could we make drastic changes to the way in which mining waste is managed such that a repetition of failure is avoided completely? What could we do?

In this paper the authors have selected a number of high profile international failures worldwide for consideration, as background. They summarize the primary mechanisms of failure as reported by many authors, and then consider the concepts of best available practice, and best

available technology. They suggest a number of key principles which are foundational in the journey towards best available technology, and make a number of recommendations.

2 SALIENT TAILINGS FAILURES OVER THE PAST 50 YEARS

The list of failures described in brief below was selected for one or more reasons listed below:

- Severity of consequences, including loss of life and environmental damage.

- High profile and visibility.

- Ground-breaking contribution potential for avoiding future failure.

2.1 El Cobre, Chile, 1965

On the 28th of March 1965, an earthquake of magnitude 7.5 on the Richter scale caused the failure of two copper tailings dams built by the upstream method in El Cobre, Chile. A total of 2.4 million cubic metres traveled up to 12 km downstream, destroying the mining camp of El Cobre and causing over 300 fatalities. Of the two dams which failed, one dated back to construction in 1930, and was lying dormant. The second dam had been commenced in 1963 (Cabrera, 2011). The epicentre of the earthquake was 60km from the tailings failure site.

The sketch below from Blight & Fourie (2003) shows a pre-failure embankment slope angle of 22 degrees flattened to no more than 3.5 degrees post failure on the El Cobre old dam. The natural ground slope was only 3 degrees.
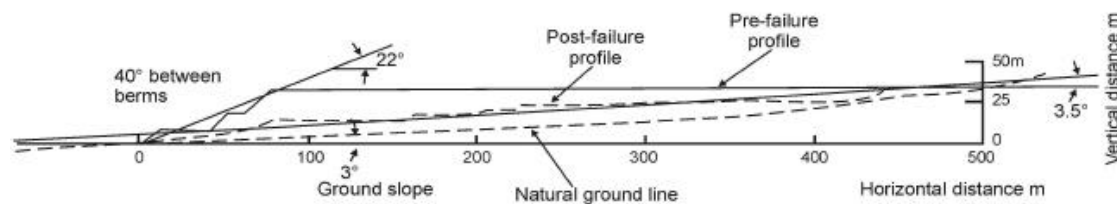

Figure 1. Pre-and post- failure profiles of EI Cobre old dam (from Blight & Fourie [2003])

As a result of the El Cobre failure, in 1970 the Chilean authorities intervened by issuing a decree (Decree No. 86) which imposed far reaching effects on Chilean tailings practice. Among the many changes were abolition of the upstream construction method for tailings dams, and requirements to apply the laws of soil mechanics to tailings dam construction (Cabrera, 2011).

2.2 Stava, Italy, 1985

On July 19th, 1985 the upper compartment of a fluorite tailings facility in the Stava Valley, Italy, operated by Prealpi Mineraia failed onto the lower compartment, which, too, collapsed, as reported by Tosatti (2003). The liquefied tailings moved downhill at a velocity approaching 90 km/h, causing many fatalities and destroying trees, buildings and everything in its path, until it reached the Avisio River. Few of those hit by this wave of destruction survived. Along its path, the flow failure tragically took the lives of 268 people and completely destroyed 3 hotels, 53 homes, 6 industrial buildings and 8 bridges. Approximately 180,000 cubic metres of material poured out of the dams. A further 40,000 to 50,000 cubic metres of the flow failure was generated from erosion, buildings demolished by the flow and hundreds of uprooted trees. The July 19th 1985 disaster in the Stava valley was the most tragic of its kind. With its toll of 268 lives lost and 155 million Euros in damage, it was one of the worst tailings failures in history.

The ministerial Commission of Inquiry and the experts appointed by the Law Court of Trento ascertained that "the settlement system as a whole constituted a continuous threat looming over the valley. The system collapsed because it was designed, built and managed in such a way as not to provide the security margins that society expects of constructions liable to threaten the

existence of entire communities. The upper bank was bound to collapse as a result of the slightest alteration to its precarious balance".

Figure 2. Aerial view of the dams at Stava before failure (ref Foundation Stava 1985'
http://www.stava1985.it/)

According to the subsequent inquiries, the collapse was caused by the chronic instability of the dams, especially in the upper one, which were below the minimum factor of safety required to avoid collapses. The upper basin measured 34 metres in height and was built at an angle of 40 degrees as an upstream tailings dam, on natural ground whose slope was approximately 25 percent.

The Commission further found "the decision to enlarge the bank according to the upstream method, which was the quickest and most inexpensive, but also the most dangerous".

The subsequent trial ended in June 1992 when 10 people were convicted of "multiple manslaughter and culpable catastrophe", and the parties involved were found liable to liquidate the damages, including the mine owners and autonomous province of Trento.

Tosatti (2003) reported further: "Besides the actions and omissions considered relevant from a criminal point of view, the Stava Valley disaster was also caused by behaviour transcending the legal dimension. For instance, there were decisions by the licensed companies and public bodies entrusted with safeguarding the territory and the safety of the people which favoured economic profits instead."

No more than 20 years after the failure at El Cobre, another catastrophic failure had claimed hundreds of lives. One of the primary contributors to the failure was the continued reliance on the upstream construction method. Except this time, not even an earthquake was required to trigger the failure.

2.3   Merriespruit, South Africa, 1994

On the night of 22 February 1994 a 31 m high tailings dam upslope of Merriespruit, a suburb of the town Virginia, failed with disastrous consequences (Wagener et al, 1997). The dam failed a few hours after 30 to 50 mm of rain fell in approximately 30 minutes during a late afternoon thunderstorm. The failure resulted in some 600 000 m^3 of liquid tailings flowing through the town, taking the lives of 17 people and causing wide-spread devastation of property and environmental damage.

Static liquefaction during undrained loading of the Merriespruit tailings contributed substantially to the catastrophic flow slide that occurred in February 1994 (Fourie et al, 2001). Why previous incidents of slope failure or overtopping of gold tailings dams in South Africa did not also result in catastrophic flow-slide failures was that much of the Merriespruit tailings were in an intrinsically unstable state in situ prior to the failure. The underlying cause was the same

reason that the failure was triggered: poor management of the tailings impoundment and particularly poor control of the tailings pond.

The Merriespruit disaster provided an impetus for both the South African mining industry and the state to take a more responsible and serious approach to disposal of tailings (Wagener et al, 1997). A fundamental re-assessment of the philosophies for design, management and operation of tailings dams was initiated in South Africa. The mining industry began to carry out independent self-audits, viewing tailings dams and associated problems far more seriously than in the past. In 1995, work started to draft an obligatory Code of Practice for the design, operation management, rehabilitation and closure of tailings dams. It was published in 1998 as SABS 0286: Code of practice for mine residue.

Figure 3. Merriespruit tailings failure (www.infomine.com)

Critical section of north wall during early stages of failure

1. Berms overtop after thunderstorm.
2. Loose tailings infill to earlier failures on lower slope erodes.
3. Tailings buttress starts to fail.
4. Pool commences overtopping and erodes slopes and tailings buttress
5. Unstable lower slope fails and failed material is washed away.

(a)

Critical section of north wall during failure

1. Lower slopes fall and are washed away
2. Domino effect of local slope failures which are washed or flow away.
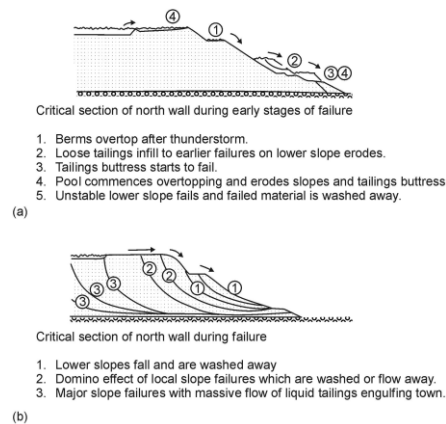3. Major slope failures with massive flow of liquid tailings engulfing town.

(b)

Figure 4. Merriespruit progression of failure (Blight & Fourie, 2000)

In comparison with other catastrophic tailings failures, the tailings volume released at Merriespruit was relatively small (600 000 m^3). However, there were many grievous human errors that contributed further to the severity and consequences of the failure:

- The design decision to locate the recycle water dam upstream of the tailings facility, thus disallowing the gravity flow of supernatant and precipitation from the impoundment to the recycle water dam.

- The planning decision to allow the construction of a mine village immediately downstream of the tailings facility in the early planning stages of the mine.

- The operational decision to combine the upper and lower compartments of the facility years before the failure, by accelerating the rate of rise of the lower compartment.

This contributed to the poor state of consolidation of the tailings in the vicinity of the failure.

- Allowance of "emergency" discharge from time to time from a bypass tailings delivery line into the impoundment without commensurate management of the inactive compartment.

- Attempts at junior operator level to solve the growing problem without communicating with management, about deteriorating pond location, slope stability and seepage, which actions could have mobilized timely interventions.

- The emergency decision in the evening of February 22nd to not evacuate the village once awareness of the incipient overtopping failure was raised.

- In the face of a low commodity price, decisions to cut expenditure on operations, surveillance and review functions designed to assure dam safety.

2.4 Los Frailes 1998

On 25 April 1998, a holding dam burst at the Los Frailes mine, near Aznalcóllar, Seville Province, releasing over 5 million cubic metres of mine tailings (Wikipedia 2015b). The acidic tailings, which contained dangerous levels of several heavy metals, quickly reached the nearby River Agrio, and then flowed into the River Guadiamar, travelling about 40 km along these waterways. The Guadiamar is the main water source for the Doñana National Park, a UNESCO World Heritage Site and one of the largest national parks in Europe. The cleanup operation took three years, at an estimated cost of €240 million.

Jon Engels in the Tailings Info website (http://www.tailings.info/casestudies/losfrailes.htm) reports as follows on the cause – a foundation failure:

The 25-m-high dam rested on roughly 4 m of river-terrace alluvium underlain by 70 m of blue marl. At a depth of approximately 10 m into the marl, overstressing of the marl beyond its peak strength by construction-induced pore pressures allowed the dam, alluvium, and shallow marl to slide along a near-horizontal bedding plane to the east (Eptisa, 1998). This resulted in liquefaction of the pyrite tailings, which in turn increased the loading on the dam as the foundation resistance was decreasing. These processes accounted for the 60 m horizontal displacement of the dam, which is considered unusually high. Other factors like earthquakes, blasting, acidic drainage, and seepage of groundwater were ruled out as contributors to the dam failure.

Figure 5. Los Frailes tailings failure (Ref http://en.wikipedia.org/wiki/Dam_failure)

The failure provoked unprecedented public outrage and international media coverage of the widespread environmental devastation. Recent media reports in 2015 continued to bemoan the failure to completely restore the damage to the ecological environment.

3 PRIMARY MECHANISMS OF FAILURE

3.1 Deficiencies in failure reporting

The number of tailings failures worldwide is substantially underreported. One could ponder the reasons. These might include an aversion to the obvious risks: litigation, reputational harm, commercial and criminal liability and business risk. One challenge might be in definition. What exactly constitutes a tailings failure? Most failures are not the result of a single cause. There are many different interpretations of what the causes or mechanisms were for an individual failure. Hindsight may be useful, but it is not an exact science. There are many papers claiming to summarize all tailings failures. According to Boswell (2015) all are incomplete, and should be read with caution. Most lists of tailings failures may be examined while asking the question: Which known failures have been omitted, and why?

There are many website lists. Some of the more useful links include:

- http://www.tailings.info/casestudies
- http://www.infomine.com/library/publications/docs/
- http://www.wise-uranium.org
- http://en.wikipedia.org/wiki/Dam_failure

Let us consider a few papers:

Rico et al, (2007) review European tailings incidents and place them in a worldwide context. They include considerations of country of location, dam height and causes of failure.

Azam & Li (2010) review causes of failure over the past 100 years, showing a peak in failures in the decades of the 60s, 70s and 80s.

USCOLD (1994) analysed tailings failures across the world and provided a quite reliable summary, at the time.

3.2 Mechanisms of failure

Blight and Fourie (2003) considered many of the published papers at the time and concluded that:

Of the known causes of failures or breaches, the most likely to occur, in order, were:

- Slope instability
- Earthquake
- Overtopping
- Foundation and seepage failures
- Structural failures, which included foundation shear, piping failure or piping through the dam wall, inward collapse of a decant tower or decant outfall.

However, interestingly, in reviewing the failures at Bafokeng, Saaiplaas and Merriespruit, Blight (2000) pointed out that these failures were not the sole result of unknown geotechnical factors or design faults (as listed above). All three were largely the result of poor operation, lack of proper management and cost saving pressures applied by the mines involved to the contractor operating the tailings impoundments. The fact that the same contractor was involved

in all three of the quoted failures, points up Winston Churchill's observation that all we learn from history is that we do not learn from history. Something more, something better, needs to be done to avoid repetition of failure.

4   BEST AVAILABLE TECHNOLOGY: DEFINITION FOR TAILINGS

4.1   An environmental term borrowed

As far as can be established, the origin of the term best available technology (BAT) can be traced to the environmental industry. Best available technology (or just BAT, Wikipedia, 2015a) is a term applied with regulations on limiting pollutant discharges with regard to the abatement strategy. Similar terms are best available techniques, best practicable means or best practicable environmental option. The term constitutes a moving target on practices, since developing societal values and advancing techniques may change what is currently regarded as "reasonably achievable", "best practicable" and "best available".

A literal understanding will connect it with a "spare no expense" doctrine which prescribes the acquisition of the best state of the art technology available, without regard for traditional cost-benefit analysis. In practical use, the cost aspect is also taken into account.

4.2   Best Applicable Practice or Best Available Technology

Before considering best available technology (BAT), it is perhaps worthwhile to first consider what BAT is not. In this paper, it is suggested that many interventions, strategies, programs and ideas are not actually BAT at all, but are rather better defined as Best Applicable Practice, or BAP.

Risk or hazard may be defined as the product of probability of failure (or likelihood) and the consequence of failure (or severity). What is needed in the tailings industry is a reduction in both the probability and the consequence of failure. It is suggested that, in broad terms, BAP is best focused on the probability of failure, while BAT may be substantially more effective in reducing the consequences of failure

Table 1 below, contextualizes some well-known concepts into the debate regarding BAT:

Table 1. BAP vs. BAT

Best Applicable Practice	Best Available Technology
"Doing things right" Focus on reducing probability	"Doing right things" Focus on reducing consequences
Management and Engineering Practices Planning and Design Construction Operations and Surveillance Independent review Guidelines and protocols Regulations and administration Safety, Health, Environment, Quality, Risk	In-Pit disposal Elimination of water Limitation of pond size Limitation of dam heights and volumes Deposition methods Chemical technologies Bright light technologies Not building dams with imponderable risk

4.3   BAT in the Mount Polley Report

It is perhaps pertinent to consider the content, conclusions and recommendations in the Mount Polley Report of January 30, 2015. The Expert Review Panel examined the historical risk profile of other tailings dams in BC and concluded that to avoid risk in the future requires the adoption of Best Applicable Practices (BAP) and the migration to Best Available Technology (BAT). Examples of Best Available Practices call for improvements of corporate design responsibilities, and adoption of independent tailings dam review boards. Examples of Best Available Technology include filtered, unsaturated, compacted tailings and a reduction in the use of water covers in a closure setting.

The Panel made seven recommendations (of which owing to interests of brevity and relevance to this paper only the first four are repeated below) to improve practice and reduce the potential for future failures. Recognizing that the path to zero failures involves a combination of best available technology (BAT) and best applicable practices (BAP), the Panel recommended the following (inter alia):

1. To implement BAT using a phased approach:

   a. For existing tailings impoundments. Rely on best practices for the remaining active life.

   b. For new tailings facilities. BAT should be actively encouraged for new tailings facilities at existing and proposed mines.

   c. For closure. BAT principles should be applied to closure of active impoundments so that they are progressively removed from the inventory by attrition.

2. To improve corporate governance:

   Corporations proposing to operate a tailings storage facility (TSF) should be required to be a member of the Mining Association of Canada (MAC) or be obliged to commit to an equivalent program for tailings management, including the audit function.

3. To expand corporate design commitments:

   Future permit applications for a new TSF should be based on a bankable feasibility that would have considered all technical, environmental, social and economic aspects of the project in sufficient detail to support an investment decision, which might have an accuracy of +/- 10-15%. More explicitly it should contain the following:

   a. A detailed evaluation of all potential failure modes and a management scheme for all residual risk.

   b. Detailed cost/benefit analyses of BAT tailings and closure options so that economic effects can be understood, recognizing that the results of the cost/benefit analyses should not supersede BAT safety considerations.

   c. A detailed declaration of Quantitative Performance Objectives (QPOs).

4. To enhance validation of safety and regulation of all phases of a TSF:

   Increase utilization of Independent Tailings Review Boards.

   The full Final Report, Appendices, and Supporting Information can be found at https://www.mountpolleyreviewpanel.ca/final-report.

4.4   Specific for purpose

One of the authors of this paper canvassed recent opinion in the international tailings industry (Anderson, 2015, Gowan, 2015, Hyndman, 2015, Johndrow, 2015, Cooper, 2015 and Wates, 2015), and concluded that for BAT to be most effective, it should:

- Be fit for purpose. (This was an almost unanimously held view).

- Take account of the site conditions - climate, geology and terrain.

- Consider the receiving environment (environmental, social and economic impact).

- Target in-pit disposal wherever possible.

- Avoid the storage of water in tailings dams.

- Recognize that cost is a significant factor.

5   BAT: FOUNDATIONAL PRINCIPLES FOR TAILINGS

5.1   Introduction

The Mount Polley expert panel report gave one example of BAT as applied to tailings structures, but the panel did not intend to suggest there was only one preferred BAT or to advocate filtered, unsaturated, compacted tailings in preference to other possible BATs. In the authors' opinion, there are a number of potential BATs that should be considered and used as applicable to each site, depending on site conditions and type of tailings. These are listed as general principles below and discussed in greater detail in the following sections.

1. Reduce or, if possible, eliminate water from the tailings prior to or during disposal.

2. Avoid storage of water within tailings facilities.

3. Minimize pond size / optimize pond location.

4. Avoid inherent failure modes.

5. Design for / use inherently stable structures and/or enhance the stability of structures.

6. Deposit stabilized tailings.

7. Reduce risk by compartmentalization.

8. Avoid the risk of cascading failures.

9. Pursue in-pit or underground disposal.

10. Approach very high or extreme consequence/risk with extreme caution.

5.2   Reduce or eliminate water from the tailings prior to or during deposition

Since the largest impact on the consequences of a tailings dam failure is the fluidity of the pond contents, it makes sense, to the extent possible, to remove water from the tailings prior to or during deposition. While filtered tailings, as recommended by the Mount Polley expert panel, is one example, there are other potential technologies (filtering is included in this list for completeness):

1. Filtered tailings – in addition to traditional filtering methods, such as a filter press, interesting progress is being made with in-line filtration methods (that is, filtration through the conveyance pipeline wall just prior to discharge / deposition; Zhang et al, 2009).

2. Traditional (in-tank) or in-line flocculation to increase the solids content and the strength of the tailings (which may necessitate the move to positive displacement rather than centrifugal pumping, or even to belt or truck conveyance; Jeeravipoolvarn et al, 2009).

3. Compaction of tailings during or after placement (e.g., "track-packing" of cells and beaches) to improve density and reduce liquefaction potential.

4. Use of additives to reduce fluidity and improve strength after deposition – one interesting technology that falls into this category, which has been investigated for oil sand tailings, is the Soane ATA process (Moore et al, 2014).

The list of available treatment technologies for reducing or eliminating water from tailings is long, as was discovered during a "tailings technology roadmap" exercise in the oil sand industry (Sobkowicz, 2012). Some of the technologies are proven in a mining or wastewater treatment setting, but many are unproven and still in a research or development phase. The difficulties associated with bringing evolving technologies to fruition are discussed in Sobkowicz (2013) and in Sobkowicz, Boswell and Gidley (2014).

Removal of water from tailings is of course a noble idea, but can be extremely difficult especially in the presence of high clay content (oil sands and diamond fine tailings).

5.3   Avoid the storage of water within tailings facilities

There is no doubt that the consequence of the Mount Polley failure was exacerbated by the amount of water being stored in the tailings pond. Closely tied to the previous point, to avoid a failure resulting in a destructive outflow, the design should provide for holding a minimum amount of water on the deposit and the facility, and for rapid drainage of rainfall and run-on water during and after a storm (Blight and Fourie, 2003). The extent to which this can be accomplished depends in part on the type of tailings pond (closed perimeter, or side hill / open sided) and the efforts made, in the latter case, to direct surface water flows away from the pond.

In many facilities, there is a need for re-cycle water, which is returned to the plant for reuse in the extraction process. Re-cycle water ponds often have extended lives, operating for decades. In keeping with the principle espoused in this section, it is desirable to design re-cycle water ponds that are separate from tailings storage facilities, in which the dams are designed to water dam standards. Water accumulating in tailings facilities should be transferred to the re-cycle water pond as quickly as possible.

Another important issue in this category is the accumulation of water within a mine over time – the so-called water inventory. If this is allowed to happen (for whatever reason – regulatory, cost, by choice, etc.), the ability to find "safe" storage locations will decrease with time and the likelihood of a Mount Polley-type failure consequence will increase. Alternatives to storing water should be found early in the mine life. The wastewaters associated with the mining process (or with collection of surface water or groundwater from the mine) will likely need some treatment before they are suitable for discharge to the surface environment or to deep aquifers, for re-use in the mine, or for use in adjacent industrial facilities. Both the treatment of wastewater and the method of discharge / disposal will benefit from the use of BAT, e.g., the latest technologies for de-salinization or the removal of harmful organic chemicals, and similarly to the geotechnical world, use of the latest technologies for monitoring the impact of wastewater disposal (on both surface water and ground water).

5.4   Minimize pond size / optimize pond location

The consequence of run-out of fluid tailings or water if there is a dam failure (all other things being equal) can be reduced by:

1. Keeping the size of any pond with fluid content as small as possible – this could apply to pond area and volume and/or to dam height above surrounding natural ground.

2. Locating any pond with fluid content below ground (i.e., in-pit) or in locations where dam failure consequences would be mitigated by the surrounding ground (e.g., no adjacent or nearby streams or lakes), structures, or land use restrictions (e.g., no inherent threat to life, environment, infrastructure, etc.).

There is often a temptation, in open cast mining operations, to minimize mining costs by placing solid waste in-pit, which is a short haul for the mine trucks. However, this cost saving must be balanced against the very real needs of tailings disposal, wherein some in-pit space must be preserved for deposits that will either in the short or long term be weaker and more prone to causing damage if located in out-of-pit, above natural ground ponds. The needs of safety must be respected. Judicious placement of solid waste in out of pit dumps may also act to mitigate some potential dam failure modes, as discussed in item 2 above.

Often not recognized as a failure mode is the poor performance of liquid or very weak deposits in a closure landscape – problems such as flow out or excessive settlement of unconsolidated materials decades after the end of mining. While minimizing pond size and optimal siting (during mining) can help to mitigate these long-term problems, more specific technologies to allow early capping, increase consolidation rate or stabilize deposits are also helpful. Closure costs can be astonishingly high when implementing BATs to mitigate these issues.

The following discussion, taken from Blight and Fourie (2003), only serves to emphasize the many mistakes that have been made in the past regarding locating or "siting" tailings ponds:

"Many waste deposits whether of hydraulic fill tailings, 'dry' mine waste or municipal solid waste are sited in positions that invite the occurrence of disasters. Examples are the Jupille, Aberfan and Quintette Marmot waste dumps, and the El Cobre, Mochikoshi, Stava and Merriespruit tailings impoundments, all of which were sited on hillsides or hill crests above villages; the Bafokeng tailings impoundment, sited 200m from an unprotected mine shaft; and the Istanbul municipal solid waste dump sited on the crest of a very steep slope. These are obviously unacceptable sites for structures of this type. In all likelihood, most of these sites were chosen for reasons of cost saving, or to use land that was regarded as waste land, unsuitable for any other use.

Examples of "waste land" that is still often used for waste disposal, but should never be so used are:

1. Steep hillsides or the crests of hills above steep hillsides.

2. Water-logged swampy areas, or areas crossed by streams.

3. Areas below the 500 year flood level.

4. Under-mined areas.

5. Areas crossed by usually dry valleys that could convey raging torrents in exceptionally wet weather.

Side-hill dumps are often opted for because the top of a ridge may be easily accessible, and dumping can proceed by building out a horizontal platform using edge-tipping with gravity to transport the waste down the hill, over the "wasteland". This was the reason for the choice of the Istanbul site and several others like it, as well as the Quintette Marmot site. The Durban Bulbul landfill was sited in a steep-sided valley. This caused seepage from the hillside to be directed towards the waste body in addition to providing a steep base for the landfill to rest on.

Siting of waste deposits in swampy areas has been the root cause of many failures (e.g. Blight 1997). In 1970 a tailings dam collapsed into underground workings in Zambia, trapping and killing 89 miners in the workings, and this was also the cause of the failure at Inez, Kentucky in 2000. The Bafokeng tailings dam was sited with one of its outer dykes on the bank of a dry valley, and it was the presence of this valley, carrying water after rain, that caused the 42 km long flow of the escaped tailings."

5.5   Avoid inherent failure modes

To start this section, it is worthwhile reviewing some very wise comments from Blight and Fourie (2003), who noted that waste deposits are among the most difficult of geotechnical structures to design, manage and operate. There are a number of reasons for this:

1. Most tailings impoundments, mine waste dumps or landfills, have an operational life of 30 to 50 years or more.

2. During their operational life, they are continually under construction, and will experience several complete turnovers of design, supervisory and operating staff.

3. Most of them have to be designed and commissioned before the material they are intended to store has been produced.

4. In most cases the characteristics of the waste will change with time, as the geology of the ore body varies and metallurgical or extraction processes are changed.

5. Many of them will eventually be constructed to heights, or will extend laterally to extents not envisaged when they were planned.

6. In mining operations, waste disposal is at the tail end of the process, and is a source of cost, not revenue. Waste disposal is therefore low on the list of priorities, both in terms of capital and running expenditure, and in terms of the quality of operating staff assigned to waste disposal.

7. At the end of the operating life, the waste deposit is still there, and has to be closed, rehabilitated, maintained and monitored for periods often thought of in terms of decades or centuries, but in reality, in perpetuity. There is no walkaway solution to closure. For example, in Johannesburg, tailings dams and mine waste dumps operated by companies that ceased to exist before the end of the 19th century, are still causing pollution and nuisance at the start of the 21st.

For all of the reasons listed above, it is critically important to avoid the inherent failure modes listed in Section 3.2 of this paper (slope instability, failure under earthquake loads, overtopping, foundation and seepage failures, and structural failures). BAPs exist for undertaking engineering design and controlling construction, to prevent these failure modes, and in many jurisdictions there are regulations or guidelines for implementing dam safety management systems and auditing both the design and performance of dams and related structures.

So, how does the use of BAT also help to avoid inherent failure modes? The geotechnical design of tailings facilities requires reliable information on the properties of the ground on which the facility will be built and of the construction materials themselves. The design will also, in many cases, be carried out using the "observational approach", which allows the design engineer to cost effectively control the risks associated with the unknowns of the aforementioned properties. These all employ the geotechnical engineer's stock in trade – drilling, sampling, laboratory testing, installation of instrumentation, monitoring, collection of performance data, and data evaluation. In all of these areas, the use of BAT, or in some cases what might be called "most appropriate technology", will greatly enhance the probability of avoiding failure. A few examples will perhaps best illustrate the point:

1. To optimize costs in a site investigation, a geotechnical engineer may elect to use a combination of drilling and in situ testing techniques to gather information. These might include CPT testing and sonic drilling to gather general ground data, triple tube coring for undisturbed sampling of stiff to hard soils, or a variety of custom designed samplers for soft soils. In situ testing might include vane shear for undrained strength, pressure-meter tests for stiffness and strength, or several different kinds of in situ stress measurement methods. The selection of the BAT will depend on the ground conditions in each site and the type of information required for design. Success at this stage will depend strongly on the engineer's

understanding of the local geology, particularly in cases of complex geology, such as soils that have been glacially deposited or modified.

2. Careful logging of core, an often under-appreciated task, may make the difference between understanding or completely missing ground conditions. Geological logging techniques are not sufficient; specific geotechnical techniques that allow identification of small but controlling weaknesses in the ground must be employed. This might be assisted by special geophysical logging methods as well, but the primary "technology" must be a well-trained, experienced eye.

3. The selection of laboratory testing methods to determine soil properties is equally difficult and important. While standard testing for soil classification, stress history and compaction properties will commonly be performed, the application of more specialized laboratory testing techniques will be a technology choice that can make all the difference in the design to prevent failure. This will include recognizing the testing techniques needed for very soft soils, stiff fissured soils, or soils containing inherent weak zones. It will also include knowing the appropriate stress conditions to use for each test. Special technologies such as large strain consolidation testing, consolidation tests driven by imposed hydraulic gradients, staged triaxial testing or triaxial testing under unusual imposed stresses, and direct simple shear tests, all have an important place in certain types of problems.

4. The installation of geotechnical instruments is a constantly evolving field, as new techniques are developed to meet unusual ground conditions. Installation to depths greater than 100 m, with high in situ pressures and/or temperatures, can be extremely challenging and require custom technologies. Appropriate methods of installing piezometers to obtain quick and reliable measurements are still under debate in the geotechnical community, particularly in low permeability soils.

5. Relatively new instruments for monitoring ground movements, such as "SAAs" (shape accelerometers) and fibre optics, hold great promise for an improved understanding of ground behaviour. These are coupled with new data logging and data transmission technologies that allow near real time feedback of the performance of tailings structures, which provides much better control in preventing failures during construction or under various operating scenarios.

6. Software, which allows improved and faster data assessment, is also important in preventing failures. Field data can now be grouped and plotted quickly and geo-referenced. The software can automatically provide an alarm when data goes beyond certain limits, such as exceeding a total amount or rate of movement, or rate of flow, or increase in pore pressure. These new technologies all allow the engineer to evaluate data faster and with a better comprehension of the actual structure performance.

It should be clear from this discussion that the geotechnical engineer's work flow, from site investigation and laboratory testing, to design and then monitoring during and after construction, is firmly focussed on preventing failure and in the process is intimately tied to the use of BAT for the tools employed to do so.

5.6   Design for / use inherently stable structures or enhance the internal stability of structures

This item relates mainly to the method selected for constructing a tailings dyke. Construction by a centerline or downstream method results (ideally) in a dam structure with a controlled density and strength, and an optimally located and constructed seepage collection system. Construction using an upstream method can potentially introduce weak and/or liquefiable zones

into the dam structure and also make seepage collection more difficult. It is in dams constructed by an upstream method that the use of BAT can prove the most helpful:

1. In terms of seepage collection, deep trenching techniques have proven quite useful in installing drainage systems (pipe, fabric and gravel chimney) on the downstream slope of a tailings dam, and in some cases even on the upstream slope and/or beach (which are subsequently drained to the downstream side of the dam; (DeWind, 2010).

2. Likewise, where drainage of seepage water to the dyke toe is problematic (very flat downstream slopes, adjacent dumps, etc.), drainage pipes have been discharged to "blind" gravel boxes, in which at a later time vertical wells are installed and seepage water is pumped out (Pollock et al, 2014).

3. Despite best efforts in even well-designed dams constructed by the upstream method, at some point in its life, the tailings pond has too much water, beaches are too short, and potentially liquefiable material is deposited in zones that will eventually end up as part of the dam structure. Technologies that allow these zones to be economically identified are worth their weight in gold - the CPT has become such a tool in recent years, along with appropriate interpretation of results (Robertson, 2009, 2010). In addition, technologies such as blast densification, which allow relatively cost efficient densification of large volumes of potentially liquefiable soil, are also critical to the safety of these structures.

5.7   *Deposit stabilized tailings*

In some cases, it is possible to stabilize tailings by adding a chemical in-line, which will improve strength and stiffness without necessarily changing water content, once the tailings have come to rest in the deposit. One such technology, considered for use in oil sand and gold tailings, is Particlear™, (Godbille, 2014; Moore, 2014). This additive works by forming a network of nano-sized silica particles within the water phase of the tailings, which immobilizes the solid particles and of itself imparts both strength and stiffness to the tailings.

5.8   *Reduce risk by compartmentalization*

Storing fluid tailings in smaller "compartments" can reduce the consequences of failure. That is, dividing what might be one large tailings pond into smaller compartments by the use of internal berms, reduces the amount of fluid available for run out during a dam failure. Better still, as discussed in Section 5.4, locating these small fluid storage ponds below ground and in non-adjacent areas, surrounded by wide zones of other solid waste, reduces even further the potential consequences of any dam failure.

This approach is discussed in detail in "De-Licensing of Oil Sands Tailings Dams, Technical Guidance Document" (Oil Sands Tailings Dam Committee, 2014), wherein a risk-based approach is used to assess both the consequence and likelihood of failure of former tailings dams to demonstrate that any remaining fluid containment is stable in a closure landscape. The methods for assessing this technology are described in detail in this document.

5.9   *Avoid the risk of cascading failures*

At some mines, tailings ponds are built in a progressive fashion, adjacent to one another and located either uphill or downhill from the previous pond. There are obvious issues related to cascading failures with this type of arrangement, which should be assiduously avoided.

While BAT might be used to monitor the performance and stability of such structures, the pond arrangement makes them inherently vulnerable to magnifying the consequences of failure compared to a single structure (see discussion in Section 5.11). The point here is that there is no BAT that makes this type of arrangement acceptable.

5.10 Pursue underground disposal

Further to Section 5.4, if underground storage is available, it should be considered either for fluid tailings or better still for stabilized tailings. This is not an option at many mines, but might be for some. The advancement and increased use of tailings backfill technology as a reliable and established technology over the past decades is most gratifying, with many conferences and papers devoted to the topic. One of the short courses at this conference covers this topic, and it is not traversed here in any more detail. Careful thought however, should also be given to the impact on surface tailings management, of the introduction of backfill operations (Boswell, 1990).

Furthermore, at some mines, it may be acceptable to dispose of wastewater in deep aquifers. This is a subject worthy of its own paper, and as such will only be mentioned in passing here.

5.11 Approach very high or extreme consequence/risk with extreme caution

While there is a lot of science, there is even more of an art in the practice of geotechnical engineering. You can believe you have done everything right in terms of site investigation, in situ and laboratory testing, design, construction control and performance monitoring, and perhaps you have! But no matter how conscientious you believe you have been, it only takes one serious failure to drive home the learning that there are large uncertainties involved in geotechnical engineering and mistakes can lead to disastrous consequences.

Mature geotechnical engineers develop a very sensitive nose for risk and learn to be very cautious in their practice – *the higher the consequence of failure, the more cautious one needs to be*. This paper has discussed some of the BAPs and BATs in the geotechnical engineer's kit bag – a cautious engineer will remember all of them and use them frequently.

One tool that has not yet been discussed is the evaluation of risk, varying from simple lists of risk, to Failure Modes and Effects Analyses, to full-blown risk assessments. This tool really belongs in the BAP category, but in applying the tool, it is important to keep in mind the BATs that will help to define ground conditions, failure modes, consequences of failure, suitable monitoring methods, and effective prevention and mitigation measures, (most of these have been described in previous sections).

There is a school of thought that suggests that structures with extremely high (i.e., "imponderable") consequences of failure should simply be avoided – that no low level of probability can reduce the risk to an acceptable level. Robertson (2011) suggested that the maximum height of hydraulic fill structures worldwide has been doubling every third of a century, and that contained waste volumes have increased tenfold over the same period. He argues that the increase in potential risk for the largest dams has increased 20 fold per 1/3 century. Caldwell and McPhail (2009) report anecdotal evidence in the platinum industry in the 1970s which limited maximum tailings dam height to 30 metres, after which a new facility was commissioned each time.

5.12 BAT - Conclusions

It is clear from the discussion in this section that both short and long-term issues need to be considered when designing and constructing tailings facilities to prevent the often severe consequences of tailings dam failure. The use of BAT may help the engineer in the site investigation, design, construction and performance monitoring tasks. They may also be used to directly improve the performance of tailings as discussed herein.

However, BAT should never be employed as a band aid to delay necessary expenditures to the end of mining or beyond (closure) – the "I'll pay you Tuesday for a hamburger today" approach. The tailings dam designer does not want to follow the example of Wally in one famous Dilbert cartoon: "I narrowed down the options to an alternative that costs too much and another that

won't work….next week I plan to think about the option of using technology that isn't available yet", (originally published on 4 August 2007).

The prudent geotechnical engineer will keep in tune with the latest technological developments in the field and with how they are being applied, and will give careful consideration to how they can be employed to improve the characteristics of the tailings deposits being developed.

As Ugo Betti once said, "There is no forgiveness in nature". We should be relentless in our determination to define and understand the "known unknowns", and to discover and be prepared for, as much as is possible through good practice, the "unknown unknowns" in our field of endeavor. Even the slightest lapse in our attention may otherwise prove disastrous. This requires a well-integrated approach by all parties to the undertaking – the regulator, stakeholders, company senior management, engineers, constructors and those monitoring and evaluating tailings performance. As noted in Sobkowicz, Boswell and Gidley (2014), the solutions are not just or even mostly technical, but are also governmental (regulatory), social and managerial.

6 RECOMMENDATIONS – CHANGE NEEDED

What conclusions may be drawn from our consideration of this topic and what recommendations for real change should we make?

6.1 *We should not be building tailings facilities with imponderable consequences*

If the consequences of a catastrophic failure would repeat a Stava or an El Cobre, then no matter how small the probabilities of actual failure are, the design should be completely revisited.

6.2 *Employ a formal process for evaluating designs to reduce risk*

In much the same way that a value engineering process is applied to an engineering design, to improve the cost benefit, so we should employ a much more formal process for evaluating tailings designs to fundamentally reduce risk.

While processes such as Failure Modes and Effects Analysis (FMEA) are useful, they cannot be allowed to merely develop a register of risks and mitigation measures for an existing design. The risk reduction requirements should address all aspects from early scoping through technology selection, to closure.

6.3 *Implement systems that proactively inform of risk*

In line with the recommendations from the Mount Polley report (and an insistence that business as usual is no longer acceptable) and the current revision of the MAC guidelines, we should be instituting management systems that proactively inform senior management and boards of directors of high risks or escalating levels of risk.

6.4 *Make provision for innovation*

Innovation is what leverages the world of technology to solve our world problems. Any consideration of BAT should therefore make active provision for the innovation, improvement and step change that technology affords. Reference is made to the paper by Sobkowicz et al (2014) in which a call is made for a Social Roadmap: ingenuity in the way our social organization as an industry must be realigned to facilitate collaboration in tailings technology which really produces results instead of spinning wheels for decades.

6.4.1 *Entrench consideration of BAT in all planning guidelines*

All new projects and those facing substantial expansion should be obliged to consider and report on the potential for incorporation of BAT into the tailings design, and BAP in the construction, management and operation of the facility. We are not suggesting a prescriptive approach, in that

specific BATs or BAPs are designated, but rather that a process for appropriate consideration of applicable BATs and BAPs is put in place.

6.5   Select technologies that reduce long term risk

Much as we would hope for as engineers, there is still no one silver bullet or panacea technology which will solve all problems.

Instead our approach should be to ask ourselves for each project:

- What are the critical risks?

- How can they be controlled?

- What technologies should be selected accordingly?

7   ACKNOWLEDGEMENTS

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http://www.infomine.com/library/publications/docs/

http://www.wise-uranium.org

http://en.wikipedia.org/wiki/Dam_failure

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