

# REVISIT TO OLD SOUTH AFRICAN SLIMES DAMS & WHERE WE ARE TODAY

Jack Caldwell, Robertson GeoConsultants, Vancouver BC  
Gordon McPhail, Metago Environmental Engineers (Australia) Pty Ltd, Perth

## ABSTRACT

In the 1970's the authors designed and built slimes dams, now called variously tailings impoundments or tailings storage facilities, in South Africa. We have also designed and overseen construction of tailings impoundments in North American and Australia. In this paper, we look back at the design and construction of some of those old slimes dams and the new tailings facilities we are involved with. We use this historical review to focus on the changing perspectives of the impact of water on the design, operation, and closure of tailings facilities. We describe the technical approaches that guided our design to highlight how in the 1960s drains were introduced by Professor Jennings to deal with the water that bedevilled every slimes dam. We describe how design approaches evolved to better deal with the water and the extent to which these have been successful. Hence we proceed to reflect on how the past has brought us to the present when there are multiple opportunities to avoid the issues of the past, design impoundments for closure, incorporate the essentials of sustainable development, save precious water, and create tailings storage structures that are more stable.

## THE BAFOKENG SLIMES DAM IMPOUNDMENT SITE

Our careers as geotechnical engineers designing tailings impoundments begun with the failure of the Bafokeng slimes dam at the Impala Platinum mine in the Bushveld of South Africa in the early 1970s. The side of the slimes dam gave way; the tailings and water in the pool on top of the dam flowed out; thirteen people in a nearby shaft were killed as the slimes rushed down the shaft; the slimes flowed nearly 50 miles downstream to fill the local water reservoir.

First Professor Jennings got us involved in collecting data to evaluate the failure. Oskar Steffen got us involved in designing a new slimes dam to replace the one that failed.

Many technical papers have been written explaining the reasons for the failure. Most people disagree with each other why the dam failed. Some say there was piping of water through the coarse tailings sandwiched between layers of fine tailings. Some say it was static liquefaction of overstressed sandy tailings.

As designers of the new impoundment we had to have a theory of failure in order to design a new slimes dam that precluded repeat of the failure of the old. Without striving to add to the debate over the causes of failure, we still adhere to this simple cause as propounded to us by those who were working on the dam the day it failed: The mine, like all mines in the area, was perpetually short of water, so they stored as much water as possible on the top of the impoundment.

The day of the failure, the pool was very close to and some say lapping up against the outer dike thrown up to make a place for the discharge pipes and the next lift of tailings discharge. Then it rained. The bulldozer driver was sent to shore up a vulnerable-looking part of the outer dike. Who knows: maybe he vibrated the wet tailings and they liquefied; maybe he dug too deep or too inexpertly with his bucket as he struggled in the rain to do something unfamiliar and he just took away the freeboard; maybe some profound geotechnical occurrence happened deep in the tailings. Regardless, the water and liquid tailings flowed out, flowed far, and killed miners.

We walked around and climbed around that failure zone measuring the thickness of the layers of fine tailings and coarse tailings. We measured the size of the breach and estimated the volume that flowed out. We took samples all the way down the debris flow trail. The lawyers fought and the words flourished. But we noticed a funny thing: nowhere in the area was there a platinum slimes dam over about 30 m high. One operator said to us: "At that height, they just don't work good any more. They are more trouble than they are worth—so build a new one"

And we noticed that there were no drains in the old ones that failed: the entire outer zone exposed by the failure was wet—or at least very moist in the soil classification system we knew and used.

## **OTHER PLATINUM SLIMES DAM**

Before we proceed to describe the new slimes dam we designed to replace the one that failed, let us record some observations at a few other platinum slimes dams we worked on. We honestly cannot recall their names or who owned them, so we simply refer to them as Dam A and Dam B.

The owners of Dam A called us in one day and told us he was worried about the stability of his slimes dam: it was approaching 30-m height and there were reports from the operators of cracks near the crest. We went to site, installed piezometers, and urged the mine to keep the pool of water far back from the crest. One late Friday, we received the first piezometer readings. It was obvious they were too high for safety, so we put a late call through and made an appointment to be on site the next Monday. Recall how difficult it was to get a telephone call through on a Friday afternoon in South Africa in those days---we had done our best.

On Monday morning we arrived on site early. Too early for our appointment with the mine, so we took a quick drive around to the slimes dam. To our horror, as we turned the corner all we could see was a classic slope failure. The slope had failed on Sunday evening. Lucky the pool was far back and only the dry tailings had slide out on the weak, black clay that is so universal a feature of the area and the foundation of most of the dams in the area. We knew that its peak shear strength is about ten degrees—just perfect for a basal failure when the tailings are about 30-m high and wet. The dam was abandoned and not used again to our knowledge.

Dam B happened to be close to a weekend cottage we used regularly. We were entertaining a visiting American tailings engineer and had arranged to take him over the weekend to see this closest local platinum slimes dam before returning to Johannesburg where he was scheduled to give a talk to the Society of Civil Engineers. Sunday afternoon I drove the American to see the slimes dam. I had on route told him of Dam A and how the black clay was prone to foundation and basal failure. To my horror and amazement, as we rounded the corner of the dam, we saw a huge

earthmoving operation in progress. Apparently some tailings supervisor and his buddy, having heard of Dam A, had decided to keep themselves and their buddies busy that weekend excavating all the black clay at the toe of Dam B and to replace the clay with rock from the mine's waste rock dump. There before our eyes was a 1,000-ft long trench where the foundation clay had been removed along the toe of the slimes dam's outer slope.

Replacing the weak clay with strong rock is a good idea; removing what little toe support the clay offered is an extremely bad idea. I finally located my engineering contact playing cricket; I dragged him under protest off the field; and drove him to the dam to countermand the supervisor's ill-considered actions. The dam was still in operation last I checked. But I still wonder if the Bafokeng failure was not just a basal or foundation sliding event; the clays at all three sites are identical.

## **THE NEW BAFOKENG DAM**

We clambered into the back of a backie, or pick-up truck in North American terminology. And we set off to drive the eleven miles of the perimeter of the area designated back in the office for the new Bafokeng slimes dam. There really was nothing to see: the ground rose slightly to the north east, but was otherwise without topographic expression.

The same black clay covered it all. I am told the clay is the result of weathering of the underlying norite in which the platinum occurs. Some say it has taken since the beginning of the Cambrian for the 1-m thick layer of clay to develop. Its Plasticity Index (PI) is well over 80, so in the winter it dries and shrinks and large tension crack develop almost to the bottom of the layer. With summer, the rains come. The clays wet up and swell; the cracks close and the surface heaves. Put a pipe or the foundation for a fence post in the clay, and two or three years later the clay turn-over will have pushed the pipe and footing to the surface.

It was a simple matter to establish the low strength of the clay. It was all residual: in effective stresses we used zero cohesion and ten degrees friction. It was an equally simple matter to calculate the factor of safety of a sand embankment on this clay. We had Dam A to validate our calculations. It was easy to show that at a height of 30 m with any appreciable water table, such a slope is not stable.

The problem with the new site, however, was that at a maximum height of 30 m, we could use only a small part of the site. The difference in elevation across the site was almost 30 m. We had to do something different while sticking to the tried and trusted.

The solution lay in two tricks:

- A series of 30-m high impoundments along the downgradient perimeter of the site, essentially forming a berm for the inner, or main part of the dam.
- Lots and lots of drains to control the phreatic line or water table in the slimes.

In those days, the start of a new slimes dam was a simple earth dike pushed up to about 1 to 2 m high. From this the tailings were discharged. This usually meant the tailings had to go uphill---which of course they preferred not to do. They hung around the starter dike and the fines settled out in layers to form low permeability layers of weak material. Trouble is those low permeability layers settled out on top of any drains placed at ground level and promptly blinded them.

Our solution was joked about and we were teased--but the approach worked. This is what we did: place a series of outlet pipes in trenches going from well inside the new dam to the exterior perimeter; lay a gravel drain on the ground; proceed with initial slimes deposition, which of course pretty much blinded the initial gravel layer. But we persisted thus: continue to deposit the slimes until a sufficient beach had built up and the fines were pushed by natural flow back into the dam and were no longer settling near the outer dike. At that point go in and lay another gravel drain and connect it to the underlying drains with a series of what we called chimney drains.

This detail did the trick. We installed piezometers, the old fashioned open standpipe type, and found no significant water table or phreatic line. Occasionally the outlet pipes would gum up with a biological precipitate which was readily removed with a high pressure water hose. To our knowledge the systems are still operating.

## **KIMBERLITE TAILINGS DAM FAILURE**

Construction of the new Bafokeng impoundment was underway, and we were sent to Kimberly to consult on a new slimes dam for the Big Hole or thereabouts. For as long as anybody could recall,

the slimes had been discharge from a single point and allowed to flow wherever it wished. And this it did; it had flowed miles over the gently sloping ground. Because it showed no intention of stopping, understandably, many years before some enterprising slimes-man had pushed up a long one to two meter high dike along the perimeter to catch the stuff.

But even that was now in danger of being overtopped. The mine had decided they needed a new slimes dam. The obvious place was on top of the old one; preferably near the discharge point where in theory the slimes should have been coarser. But this is a diamond tailings---it is not coarse in any part of the gradation curve. The sun had, however, beaten down for years and years and dried out the tailings, forming a reasonable foundation.

We designed something with drains and pool control and all the bright new ideas we were flush with from the Transvaal. But the miners would have none of these new-found ideas from the liberal north. *No Drains---We Will Control The Water* was their mantra. It took only one lunch at the Kimberly Club to persuade us to acquiesce.

The dam was built and operated for a few years. But the inevitable occurred: the miners lost control of the pool which came too close to the edge and it all failed. No real environmental harm and the materials running out of the breach simply continued on down and over the old tailings deposited for decades in an uncontrolled way. The replacement dam included drains.

This case history along with the story of the Bafokeng dams reinforced the need to provide drains, control seepage within the tailings outer slopes and limit the quantity of water on the top of the impoundments. None of these lessons learnt fully entered the system and some years later, after we had both left South Africa, the slimes dam at Merriespruit failed for much the same reasons as had caused the failure of the dams we described here. .

Other tailings dams have continued to fail worldwide with alarming regularity for the same reasons as those early South African dam failures.

## **MT TOLMAN, GREENS CREEK, AND CANNON MINE**

One of us moved to the United States. There we faced demands for far higher tailings impoundments in far less hospitable climates than in South Africa. The first dam we designed was for a proposed molybdenum mine called Mount Tollman in northeast Washington State. The mine never got off the ground and our design was never built. Yet for this tailings facility we designed and had approved by the regulators a 300-m high embankment, the lower 100 m of which would have been rockfill and the upper 200 m of which would have been tailings cyclone underflow placed and compacted into paddocks.

Then to Alaska and Greens Creek on Admiralty Island just off the coast of Juneau. Here is perpetual rain. We could find no way to control the excess water. The obvious solution was to dewater the tailings, add a little cement, and place as a dry pile. This is still being done today.

Finally to Wenatchee, Washington where we designed and spent two years on site overseeing construction of the Cannon Mine tailings impoundment. We write of this facility in a separate paper in this proceedings, but for the purposes of this paper, note that we chose a compacted rockfill berm with low permeability core and adjacent filters. All the details you would expect for a facility directly above the town and built on foundation bedrock much the same as those at the Teton dam that had failed some years before as a result of uncontrolled seepage and hence piping through the friable sandstones of the foundations.

By now we had grown so conservative about water control and tailings encapsulation that we got the job of managing engineering design of the closure works for the uranium piles of the Uranium Mill Tailings Remedial Action Project. We have written extensively about the engineering details of that project and in this conference take a look back at how these piles have performed in the nearly twenty years since their construction. In a word: well, proving one can reclaim tailings piles that have no pond and little water, although the costs are high.

## **AUSTRALIAN PRACTICE**

One of us went to Australia where we soon learnt that there is a dearth of water. Almost every mine is under severe constraints to limit water losses. Thus we became interested in high density thickened tailings deposition.

Tailings is considered to be 'high density' when the percentage solids in the tailings slurry is increased to 65% to 75% solids. The tailings density is increased by either passing the tailings through a bank of cyclones and/or a thickener. In both cases the underflow, from either the cyclones or new thickener is pumped to the tailings storage facility (TSF), the Australian term for a slimes dam, as thickened tailings and the over flow is returned to the plant or thickener.

The overflow is usually rich in chemicals (acid, cyanide, etc.) and may contain small quantities of dissolved metals which can be recovered if the overflow is re-circulated through the processing plant. The increased recovery of process water (from the cyclone or thickener overflows) will effect a saving in the quantity of chemicals required for processing, thereby giving additional 'chemical credits' for the plant. Tailings underflow can be re-conditioned to the design moisture content for pumping using centrifugal pumps, i.e., positive displacement pumps are not required for pumping of high density tailings.

High density tailings deposition has a number of significant benefits over conventional tailings deposition. These are listed below and described in more detail in the ensuing sections.

- Lower ongoing operating costs,
- Reduced water losses and seepage,
- Improved slope stability
- Reagent savings,
- Improved environmental performance,
- Reduced closure costs

Here follows a discussion of each of these factors.

### **Lower On-going Operating Costs**

Ongoing operating costs for above-ground high density facilities are reduced as civil works are limited to ongoing topsoil stripping and covering/rehabilitation of the completed areas of the TSF, limited embankment construction, construction of water management facilities (if

required) and extension of the tailings delivery pipework.

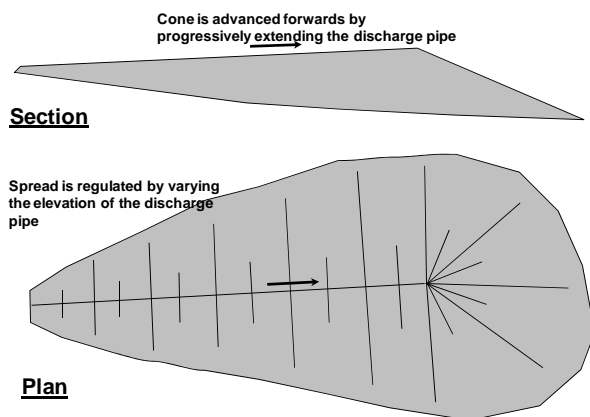
The most common method of operating high density facilities is using a single “central” discharge point that is systematically raised. Originally this method was referred to as Central Thickened Discharge or CTD although whether the discharge is indeed central depends on whether the ground is flat. The deposited tailings forms a cone around the single “central” discharge. But this method of tailings deposition has a number of drawbacks:

- It is volumetrically inefficient especially on sloping ground.
- It requires burial of the discharge pipe within the tailings and if this pipe holes there are significant erosion issues.
- It requires access to the discharge point and this access is continually rising requiring on-going capital expenditure.
- It is not possible to effect progressive rehabilitation as the tailings surface is always rising.

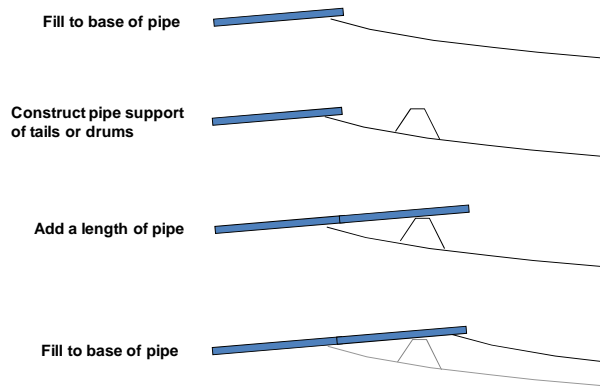
A practical alternative to the single “central” discharge method is the advancing cone method.

The advancing cone method of high density tailings operation entails the progressive advancement of a delivery pipeline upwards, horizontally, or downwards as tailings is deposited.

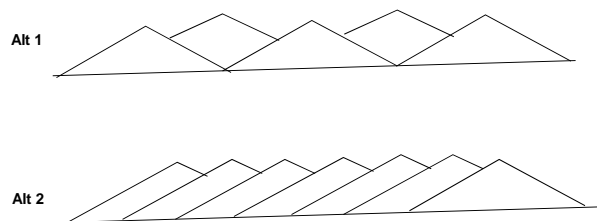
Figure 1 shows a plan and section of a typical advancing cone. Figure 2 shows a typical method of pipeline advancement and Figure 3 shows alternative methods of developing adjacent advancing cones.



**Figure 1**



**Figure 2**



**Figure 3**

The advancing cone method has significant advantages over a single “central” discharge in that:

- Volumetric storage is significantly better. The pipe can be directed to create curved embankments and/or progressively raised as long as the angle of raising is less or equal to the beach angle.
- The delivery pipeline is not buried and always accessible.
- It is practical to effect progressive rehabilitation behind the discharge point.

### Reduced Water Losses

By pumping the slurry at high density the excess of water over the initial interstitial water of the newly settled slurry is reduced – the water has simply been kept in the plant water circuit instead of being sent to the TSF. This means lower volumes of supernatant water, smaller pond areas and lower evaporation area.

Water losses through seepage are reduced as with lower pond volumes comes lower driving heads over lower areas. Above the small ponds on the exposed beaches seepage is the difference between

## Improved Slope Stability

Low seepage rates translate into low phreatic surfaces and shallow beaching angles translate into exceedingly flat slopes. Provided the density of the slurry is selected such that the material is able to consolidate to a void ratio below the critical state line there are unlikely to be any slope stability issues. Moreover, since the method of placement of the tailings relies on progressive advancement of the pipe over deposited tailings and no heavy equipment access for wall building or packing of the tailings, the allowable rate of rise can be taken to 15m/a without difficulty or risk of instability.

Only in limited circumstances, such as when impounding the high density tailings behind a confining embankment, is it necessary to provide any filter drains. Generally, in the arid climes of Australia, seepage and drainage requirements are not required.

Like all tailings facilities these issues need to be checked as a matter of design but we have not experienced problems in this regard in Australia so far.

## Reagent Savings

As a result of collecting process water directly from the overflow from either the cyclones or the thickener all excess process water is recovered and re-circulated within the plant. This recirculated water is likely to contain chemicals and reagents required during the processing of the ore, and indeed some dissolved metal, so that recirculating the water maintains concentrations of often costly reagents and valuable metals within the plant circuit. Retention of reagents translates into lower reagent top up and therefore cost.

## Improved Environmental Performance

High Density tailings disposal has a number of benefits over conventional tailings deposition. These include the following:

- Staged site clearance, minimising exposed areas (for above ground deposition).
- Reduced water requirements.
- Smaller carbon footprint due to minimal earthworks requirements during construction and ongoing development and operation of the facility.
- A water-shedding final geometry which is preferable for closure of the facility.

- An aesthetically pleasing final geometry that should blend into the surrounding environment more readily than a conventional facility.

## Reduced Decommissioning Costs

Decommissioning costs are likely to be significantly lower than for a conventional TSF as the final geometry lends itself to ongoing rehabilitation. The high density facility is water-shedding thereby negating the need for the design and construction of surface water runoff management facilities. Expected final slopes of between 1:30 and 1:50 (V:H) increase the ease of construction during decommissioning and reduce the long term erosion potential.

## Successful Documented Application

TSF2 at Barrick Osborne Mine in Queensland is a good example of the effectiveness of high density thickened discharge. This facility is based on advancing-cone deposition and entailed conversion of a conventional TSF to high density in 2003. This facility is now fully operational and heading for decommissioning in 2010 when mining operations are due to stop.

A number of papers have been presented on the Barrick Osborne tailings facility<sup>1,2,3</sup>.

That said, while we have succeeded at some sites we acknowledge that the high density approach is not for everyone. But it is the tailings management method of the future.

## CANADA

Water continues to be an issue at some tailings impoundments. A quick reference to the web and you will find much information about the Alberta oil sands which are deposited as fluid streams into impoundments created by constructing large earth dikes. The tailings are still essentially a fluid (as is described in another paper in this conference that one of us has co-authored.)

The Alberta Energy Resources Conservation Board (ERCB) last year published new regulations demanding that the industry dewater the tailings to the point that they have a shear strength of at least 5 kPa. This number they picked up from an old technical paper that claims you can drive a truck on tailings of that strength. While we doubt it, we

recognize that this was a genuine attempt to force the industry to get as much water out of the tailings as possible before depositing them. Ignoring the ERCB's confusion between trafficability and flowability, we recognize that the idea behind dewatered tailings was presumably that such tailings were not susceptible to flow down the Athabasca River as did those of Bafokeng.

Industry and academia have pointed out the many flaws with this approach to regulating placement of dewatered tailings as a way to limit their susceptibility to long-term geomorphic instability. And the ERCB is backtracking into the part of the new regulations which says to the industry "tell us what you can and will do."

There are ways to dewater oil sands tailings: additives to make CT; flocculation; and wick drains are but some. Only time will tell which is best. But we must ask in all innocence why the fuss? If the dikes are strong and society is prepared to maintain them, let the natural processes of consolidation take place. A geomorphically-induced breach in a dike impounding dewatered tailings will have much the same consequences in an untended situation as one entraining undewatered tailings.

It may be aesthetically nice to think of the tailings as dewatered, but that is an ephemeral and transient benefit. If you do not do it as the tailings are deposited, then we suggest in practice you are stuck with maintaining the integrity of the encapsulating embankments in perpetuity.

If the ERCB really wants to protect the Athabasca River, maybe they should take a leaf out of the UMTRA regulations and write:

Design, build, operate, and close oil sands tailings impoundments so that they do not breach and the contents do not flow out for at least 1,000 years to the extent reasonably achievable, and at any rate for 200 years.

Actually this or similar is the only regulation you need for any tailings impoundment. You may increase or decrease the periods. But at the end of the day that is the only reasonable regulation to force tailings design engineers to include drains, dewatering, and fluid solidification into their designs.

## VAIL, COLORADO 2008

Thus we acknowledge the many changes in tailings disposal practices in the past few decade. These changes were on full display at last year's conference in this series. Here are some of the profound changes we noted in the many fine papers from that conference held in Vail, Colorado in blinding snow.

- Liners for impoundments are now accepted as good practice; no longer do we hear how liners are unnecessary components forced on the mining industry.
- Covers are now routinely four feet and thicker; gone are the days when the proud brag was a one-foot thick cover.
- Side slopes of three to one and even five to one are considered reasonable; no longer do we hear that the angle of repose is stable enough.
- Water is a component of interest and value; no longer a side issues and a nuisance.
- Regulations including CERCLA and RCRA are mentioned in passing and implemented routinely; no longer are there tirades against unwise regulators.
- Stochastic methods are used and the young recognize that extreme events do occur.

These we consider to be good changes. Although they have resulted in significant increases in the cost of tailings and mine waste management.

## THE FUTURE

Factors that in future will contribute to even greater costs of tailings include:

- The new U.S. Environmental Protection Agency undertaking to make sure mines have sufficient funding to close and cleanup their mines.
- The need to dewater tailings prior to closure (an Alberta imperative for the oil sands industry)
- Legal fights to put tailings in lakes and the oceans when environmentalists would prefer upland piles (another Alaskan story.)
- Every increasing demands for less water consumption and import.
- Higher embankments for large tailings disposal facilities in harsher climates.

- And ultimately a recognition that you can, even if you would rather not, close the facility to be stable in the very-long-term.

## CLOSURE

We will continue to mine for the simple reason that we must. Whether we need the materials for SUVs or windmills, we must get the materials from mines. We simply cannot see how the world's ever-increasing population can be supplied by recycle alone, desirable as the aim may be. And as long as we mine, that long we will produce tailing and be faced with difficult decisions about costs, technology, and the balance of operational common sense versus the imperative to leave behind a topographic form that is geomorphically stable in the landscape we have altered.

The stories we tell in this paper reflect but a few years of mining...but they have been years in which great changes have occurred in the practice of tailings disposal. Now we must continue, but ultimately leave it to new generations to deal with the new demands of the fast changing world of climate change, water shortages, more people communicating via the web and twitter, and nationalism that inhibits mining even in formerly remote locations.

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