Are Tailing Dams Viable in the Modern Environment?

Thomas F. Bunn[1], **Tim Gilroy**[2], **Craig A. Wheeler**[1] **and Mark G. Jones**[1]

[1]Centre for Bulk Solids and Particulate Technologies
The University of Newcastle, University Drive, Callaghan NSW 2308 Australia
[2]GEM Projects Pty Ltd,
PO Box 2035, Strathpine, Brisbane, Queensland 4500 Australia

ABSTRACT Tailing dams are normally built to contain refuse from mining, mineral processing and power generation. They have been an essential part of the minerals extraction process. History shows that serious environmental and safety issues are associated with tailing dams. There are options to the conventional tailing dams that can offer remedy the problems experienced with the dams and although economically more costly in the short term, may be economically viable in the longer term.

1. INTRODUCTION

Tailings dams are an economic solution to the management of refuse. The economic cost of tailings dams is somewhere in the range from $1/t to $5/t tailings deposited, and adding societies true cost, it could be argued the cost is actually between $2/t and $10/t depending on the circumstances and what indirect costs are included. Indirect costs include amenity (physical and visual), ongoing insurance, monitoring, groundwater contamination, dust contamination, loss of real estate value in areas on and around the tailings dams (e.g. reluctance to build an agricultural industry in the valley below a tailings dam).

The main hazard the dams present is an unacceptable high historical rate of their failure which typically cause substantial losses, including loss of lives. The failures occur due to:

- Inadequate design and or construction;
- Rainfall events in excess of the design allowances;
- Seismic activity causing re-liquefaction.

The ICOLD Committee on Tailing Dams and Waste Lagoons (1995-2001) has developed guidelines for the safe design, construction and closure of tailings dams. These guidelines for the dam's construction can reduce degree of the dam failure risk. Publications include ICOLD Bulletins Nos. 45 (1982), 74 (1989), 97 (1994), 98 (1995), 101 (1995), 103 (1996), 104 (1996), 106 (1996), ANCOLD (1999).

It is of major concern that tailing dams failures continue at a high rate. Unfortunately, the number of major incidents continues at an average of more than one a year. During the last 6 years the rate has been two per year. Tailings dams are supposed to last forever, but past experience shows that minor and major spills pose a serious environmental threat that stay behind when the mine closes.

A number of characteristics make tailings dams more vulnerable than other types of retention structures (e.g. water retention dams), namely:

- Embankments formed by locally collected fills (soil, coarse waste, overburden from mining and tailings);
- Dams subsequently raised as solid material coupled with a severe increase in effluent;
- Lack of regulations on specific design criteria;
- Lack of dam stability requirements regarding continuous monitoring and control during emplacement, construction and operation;
- High cost of maintenance works for tailings dams after closure of mining activities;

- Mining industry changes mean the rates of refuse vary with market conditions (due to changes in yields from process plant and capacity of process plant), this means the planning of dam raisings is often lacking during a cyclical mining boom;
- Changes in mining and processing techniques are always occurring, and again the planning of dam raisings is often lacking due to unexpected capacity changes.

The main cause of historical dam failures was rainfall events followed by occurrences associated with seismic liquefaction. Over 90% of incidents occurred in active mine tailings dams, and only 10% refer to abandoned dams. The number of reported incidents throughout the world involving tailing dams was 221 [1], resulting in 147 tailing dam failures occurring [2].

Due to the nature of mining and mineral processing, the volumes of mining wastes are significantly larger than those of both domestic and industrial wastes. The material stored in tailings dams is usually very fine. This material is placed hydraulically, is loose and is at, or above, saturation. Any major movement of the retaining boundaries of the impoundment can induce shearing strains that disturb the structure of the tailings mass, inducing a rapid rise of pore water pressures and liquefaction of a section of the impoundment. An event like this can cause even greater pressures to be applied to the retaining boundaries. Failure of the retaining dam can release liquefied tailings that can travel for great distances, and because of its greater specific weight, destroy everything in its path. Water will flow through and around buildings, but liquefied tailings can destroy the structures. Historically the tendency is for tailing dams to become ever higher and impoundments ever larger.

Table 1 Examples of tailing dam failures

Date	**Location**	**Material**	**Results**
May 2009	Huayuan County, China	Manganese tailings	3 killed
December 2008	Kingston fossil plant, Harriman, Tennessee, USA	Coal ash	4.1 m^3 released covering an area of 1.6 km^2 to a deep 1.83 meters
September 2008	Taoshi, Linfen City, China	Iron ore tailing	245 killed, 43 injured
April 2006	Miliang, China	Gold mine tailings	Toxic potassium cyanide released into the Huashui river
August 2002	Dizon Copper Silver Mines, Zambales, Philippines	Copper & Silver tailings	1,000 families evacuated
June 2001	Mineração Rio Verde Brazil	Iron ore tailings	5 killed
October 2000	Martin Country Coal Corporation, Kentucky, USA	Coal waste slurry	0.95 million m^3 released killing fish in Tug River and drinking water intakes closed.
April 1999	Placer, Surigao del Norte, Philippines	Cyanide tailings	700,000 tons released burying 17 homes
September 1995	Placer, Philippines	Copper & Gold tailings	50,000 m^3 released 12 killed
February 1994	Merriespruit, South Africa	Gold mine tailings	6000,000 m^3 released 17 killed
July 1985	Stava, Italy	Fluoride tailings	190 000 m^3 released 269 killed
January 1978	Arcturus, Zimbabwe	Gold Mine tailings	20,000 m^3 released 1 killed
November 1974	Bafokeng, South Africa	Platinum mine tailings	3 million m^3 flowed 45km 12 killed
February 1972	Buffalo Creek, USA	Coal tailings	500 000 m^3 released 125 killed, 500 homes destroyed
September 1970	Mufilira, Zambia	Cyanide tailings	68,000 m^3 released 89 killed

2. WHY ARE WE STILL BUILDING TAILINGS DAMS?

Why does everyone keep building tailings dams? The list of reasons would include;

- Lowest cost,
- Ability to defer capital via staged construction,
- Government security bonds are usually required, and

- Can deal with variation in concentrations, quantity or weather.

A mining company can fully appreciate the cost of maintaining a disused tailings dam, especially one that can't be acceptably rehabilitated because it continues to release leachates and consolidates, thus requiring maintenance to occur indefinitely. If ongoing monitoring and insurance for a tailings dam is say \$0.01/t, the total net present value over 30 years is \$0.2/t at 5% discount rate. This indefinite cost is low and sustainable in the long term for many big mining firms who are planning on long term growth. The mining firm can rely on the fact that permanent consolidation of a tailings dam will occur, one day in the future.

Most costs are well understood, but one of the cost elements is factorised risk cost, which is the discussed in more detail in this paper.

Most decisions about tailings dams use a probability factorised cost for various potential failure events. Many tailings dams around the world today claim to have catastrophic failure probability risk at lower than one in a million.

An important lesson can be learnt from the loss of the Challenger Space Shuttle. This space vehicle was designed for a failure rate lower than 1 in a 100,000 event, and this was believed by all the experts and management before the disastrous event involving the loss of the shuttle and its crew. The post incident investigation found that the failure rate was around 1 in 100, and it there was evidence that failures were regularly occurring at this rate of less than 1 in 100 until the incident. This was an error in the failure rate estimate of 1000 times, and it was not due to poor science which was very detailed, but to the variability of human behaviour, from the designer to the operators [3].

A failure risk probability level of one in a million might be achievable for say an electronic device, which can be physically tested repeatability. But a tailings tams is not physically tested, it is like the space shuttle, the designer get one chance. So, like the space shuttle we have say four designers checking each other, and four supervisors watching every excavator and dozer. Each check might only have a 1% risk of failure, and we should have 1 in 10 million after the fourth check. But humanized risk is more like the Swiss cheese risk model, if you put four slices on Swiss cheese on top of each other that contain 1% holes, you have an unusually good chance of lining up. This is because of human processes which create each of these engineers and earth moving machine operators contain the same experiences, attitudes and culture.

The main root causes of failure of dams are unusual rainfall and unusual seismic activity. It can be hypothesised that all the expertise in tailings dams, cannot find enough data in these low probability events to properly assess this risk and therefore four independent experts have the same hole in same location on their slice of cheese.

Another hypothesis is the assessment of the impact of a failure. For example *"A tailings dam failure in 1950 emplaced metal-rich sediment at high flood-plain levels, above 50 years to 100 years flood stages in 1996 and 1997. These large natural floods removed only a small part of the contaminated sediment through bank erosion; they also failed to lower in-channel Cu concentrations, because increased erosion of mine waste during high flows balances increased inputs of uncontaminated sediments, generating no net change in concentrations. Geomorphic processes controlling movement of contaminated sediments indicate that mine impacts will persist for centuries in Soda Butte Creek and imply long-lasting impacts in similarly affected streams worldwide"*[5]. This statement runs counterintuitive to the dilution theory often used to explain those low probability extreme rainfall events. It can be hypothesized another hole in our shared Swiss cheese is our inability to recognized that a few centuries of contamination of a river system will cost huge sums of money and lost economic productivity and social disruption.

What if we reconsider the indefinite time cost of a rehabilitated tailings dam, if the rehabilitation was not entirely successful (as defined by negligible leachates escaping and maximum consolidation)? Statistically at some point in the next 10,000 years, an earthquake, volcano, 1 in 10,000 year flood, tsunami or a major event will occur at every tailings dam site. The risk of a catastrophic failure of a tailings dam, which is currently estimated as a one in a million event has a one in a hundred chance of occurring in this timeframe. And if the 1 in a million evaluated risk was in error by a 1000 times, like the Challenger Space Shuttle disaster [3], then this catastrophic failure will occur 10 times, and society will have to clean up the same broken tailings dam 10 times.

So in conclusion,

- the direct cost of a tailings dams are well known,

- the probability of failure should really be in the in a order of magnitude of one in a thousand range due to the limitations of our sociological behaviours, and,
- the order of magnitude of the cost of consequences for a catastrophic failure should be in the billions or trillions of dollars when there is any ecological system downstream which humans rely on for survival.

3. ALTERNATIVE DISPOSAL

Tailings are a mixture of particles, water and chemicals left over from the processing plant. If it is "chemically bound" it makes a soil like substance or agglomerated solids. This "bound" soil can be quite useful in construction and landfill as the noxious chemicals are locked in the matrix. These tailings can then be useful in the construction of useful manmade landforms. For example, a steep valley could be made less steep to prevent erosion or an old mine pit could be filled, making the land more suitable.

As the most common binder is cement, suitable placement characteristics can be achieved with the addition of only 2% cement by weight. At $285/t the cement represents an additional cost to the tailing disposal system of less than $6/t. The binding of particles in an inert matrix can occur through different chemical reactions. For this assessment we will assume that this binding occurs through the use of standard grade cement.

Most binders are sensitive to the presence of water, especially where the binding reaction requires a specific concentration of water such as mixing concrete using cement. If dewatering is not required then the only additional cost will be the $6/t as mentioned above. However, if dewatering is required the following additional cost will occur:

- Deep Cone Thickening (which is less than $1/t)
- Mechanical drying using belt press vacuum filters (which is less than $5/t),
- Thermal drying (which is expensive at $30/t); or;
- Adding dry material such as fly-ash or ground blast furnace reject material. The addition of this material at 25% concentration may attract a cost of $5/t.

The next cost after binding is materials handling. In normal tailings dam systems a slurry pipeline provides low cost transport with centrifugal pumps and the flexibility of a short pipeline to get to the emplacement sites. For a typical paste system with a binder, and delivery designed to create useful landforms paste pumping, or trucking is required. Pumping the tailings as a paste would add an extra cost of between of $2 to $5/t. So in summary the costs are shown in Table 2.

Table 2 Summary of costs comparison

Costs	**Tailings dam**	**Bound stabilized fill**
Direct	$1/t to $5/t	$6 + $1 to $5 + $2 to $5 =$9/t to $16/t
Indirect	$1/t to $5/t	No indirect costs
TOTAL	$2/t to $10/t	$9/t to $16/t

So clearly a bound stabilized land fill is more than twice the cost of a tailings dam.

A comparison with data from metaliferous mine backfill plants shows a reasonable correlation, which have emplacement costs of between $2/t and $30/t depending on the mining requirements, geotechnical performance, and accounting cost methodology.

4. EXAMPLES OF CHANGING AN INDUSTRY FROM SLURRY TO PASTE PRODUCTION

The disposal of power station ash in Australia has been undergoing a significant shift in emphasis during the past ten years.

In older power station fly ash and bottom ash were transported to a tailing dam in two purpose built systems.

- The first system was for fly ash (dust). The dust was removed from the boiler gas passes by either fabric filters or precipitators collection systems. The dust was hydraulically evacuated from the fabric filters or precipitators storage hoppers on either an intermittent or continuous bases and sluiced to the dust plant. In the dust plant the sluiced dust was mixed with large quantities of water and pumped using centrifugal pumps as lean phase slurry with a C_w (solids concentration by weight) <10 %;
- The second system was for bottom ash, which was intermittent dumped from the wet bottom ash hopper into a sluiceway and sluiced to the ash plant. In the ash plant the sluiced bottom ash was first crushed to < 25 mm, mixed with large volumes of water and pumped using centrifugal pumps as lean phase slurry C_w (solids concentration by weight) <10 %.

The slurry pipelines discharge into a tailings dam simply called the ash dam. The water from the ash dam is recycled back to the power station for reuse. The water used for ash disposal systems could either be fresh or salt water depending on the power station location.

For newer power stations and as a retrofit to existing stations an alternative ash disposal system is one where both the bottom ash and fly ash are mixed together and pumped as high concentration slurry to a disposal site. The fly ash is removed from the precipitators or fabric filters by a pneumatic conveying system and conveyed to a HCSD (High Concentration Slurry Disposal) storage silo. The bottom ash is removed from the boilers by a dry removal system and after passing through a hammer mill, where the size is reduced to < 8 mm, is also pneumatically conveyed to the HCSD storage silo. The ash from the HCSD storage silo is mixed as high concentration slurry C_w of 63% in a mixing plant and pumped using diaphragm pumps at a flow rate of 100 m^3h^{-1} to the disposal site in a 150 mm diameter pipeline with a pressure of 3 MPa.

In an another power station, fly ash slurry is pumped as a high concentration slurry at a C_w of 72 % at flow-rates up to a maximum of 240 m^3h^{-1} a 200 mm diameter pipeline with a pressure of 6 MPa a distance of 10 km to a disposal site. The disposal site is a disused open cut coal mine. Figure 1 is a photograph of the disposal site

While at another power station with a HCSD system there is no tailing dam, only bung walls, and the disposal site is progressively rehabilitated. Figure 2 is a photograph of the disposal site

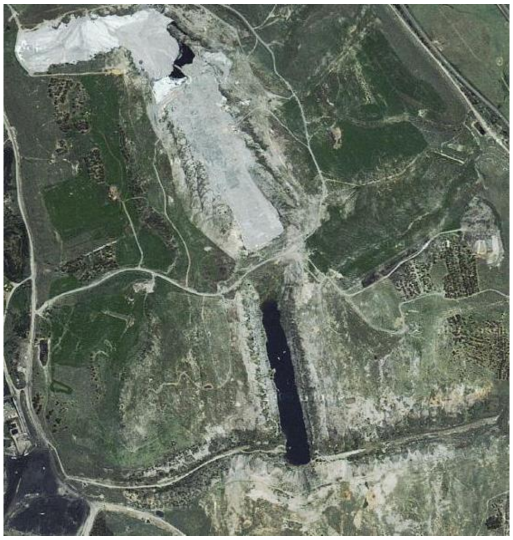

Figure 1 Disused Mine Ash Disposal Site

Figure 2 Bund Wall Ash Disposal Site

5. MATERIALS HANDLING SOLUTION FOR ALTERNATIVE DISPOSAL TO UNDERGROUND VOIDS

Using mineral process tailings to produce paste backfill with a binder is well proven and documented in specific engineering publications, such as those by the Australian Centre for Geomechanics. This field of extensive and proven commercially viable research is primarily aimed at increasing mining extraction ratios with structurally competent backfill.

An important way in which paste backfilling is beneficial is through reduction of adverse environmental effects of tailings dams. There are numerous underground mine voids being filled with tailings in Australia, South Africa and elsewhere. It is not always possible to put all tailings back underground due to insufficient underground voids; however tailings dam sizes can be significantly reduced.

Chemically bound and stabilised tailings are already status quo in metaliferous mining where improved mining efficiencies have justified the additional cost as a backfill.

In the coal industry in Europe, Deutsche Montan Technologie (DMT) developed a coal mine backfilling system that was installed in the 1990's at the Walsum Mine [4]. This mine is being backfilled with residual material from processing and combustion of coal, from incineration of domestic refuse and sewage sludge. This system had a mixing and pumping station on the surface which delivered a 100 $m^3 h^{-1}$ at 12 MPa of paste according to specific criteria to match both desired high solids content and a low pressure loss. The paste is pumped through pipes to the coal faces using powerful piston pump with a total power consumption of 480 kW. This system successfully pumps the paste up to 12 km through a 200 mm pipeline to the working face at a depth of 800 m. The paste is deposited in the goaf by using trailing pipes, the pipes are of 15 to 20 meters in length and are attached to the Long Wall miner and are trailed along during the advancing process. The paste accumulates in the collapsed mined area and does not flow to other areas of the mine. Unlike the conventional hydraulic stowing methods, there is no necessity to capture the conveying water and pump it back to the surface.

A paste for backfill can be prepared from refuse material from a coal washery, that is thickener underflow material and ground rejects. A paste pumping trial conducted at the University of Newcastle indicate the material comprising finely ground reject mixed with thickener underflow material can be pump at a C_w up to 75 %. This paste could be left in the pipeline for long periods and the pumping system restarted. This paste could be pumped long distance for depositing underground.

6. CONCLUSION

Serious review should be given to the acceptance of a tailing dam design failure rates of the order of one in a million, where numerous actual failures of tailing dams throughout the world are resulting in of loss of life, destruction of homes and infrastructure and environmental pollution. Although current practices attempt to mitigate these risks, there may be a systemic risk that the industry is telling society that "one in a million" means "you don't need to worry" is not accurate. Society has seen the scientific and engineering community suffer low probability catastrophes many times (e.g. Chernobyl, Challenger, Three Mile Island, etc), and is building skepticism towards these kind to claims. There is poor data and understanding of low probability rainfall and seismic events over the potential life spans of tailings dams, and there is probably a poor estimate of the consequences of failure due to human behaviour. The industry needs to develop alternatives.

A system of dewatered tailings, mixed with binder and placed as a paste for a desired land-fill shape, is between 2 to 3 times more expensive but has the following advantages compared to tailings dams;

- Is a significantly lower risk of catastrophic failure in both incidents and consequences, due to the bound agglomeration of superfine material by binders and that are no longer super saturated;
- Has a smaller footprint;
- Consumes less volume;
- Has greater aesthetics;
- Can be progressively rehabilitated and released for re-use; and

- Can deal with variation in concentrations, quantity or weather (although not as easily as a tailings dams);

Could society afford chemically binding their tailings? The answer is yes. The tailings cost is a small cost component of everything that is mined. To keep a level playing field for our mining companies this would need to an act of legislation from all governments around the world.

There are many innovators and solutions for chemical binders, however these solutions are unlikely to have been properly tested as they would never been able to economically compete with a tailings dam.

More testing on the leachate retention rates of various binders is the main priority for further research, which needs industry and government support to pursue this. Some binders will still require a leachate collection system and testwork is required to determine which binders are in which category.

The principle of returning the refuse to the place of origins as a backfill is a logical solution that should be pursued where possible. The principal of using dewatering, binder and paste pumping for dry-stacking new dams or landforms should be pursued to eliminate risks of tailings dams. Technologies to implement alternative methods exist and are proven. The additional cost of this could be justified by closely examining the true indirect costs.

The conceptual options which would replace traditional tailings dams include:

- Tailings as a paste can be placed without binder on a temporary surface stacked stockpile, and then placed in an open cut void after mixing with a binder;
- Tailings as a paste can be placed with a binder on a surface emplacement of a desired shape of bound stabilized fill;
- Tailings as a paste can be placed without binder as a mine backfill into old voids;
- Tailings as a paste can be placed with a binder as a mine backfill into old stopes to improve mining extraction ratios.

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