Leading versus Lagging Indicators of Tailings Dam Integrity

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ABSTRACT: Despite the best efforts of the international tailings community, experience over the past decades and in the last five years in particular, has shown that tailings dam failures continue to occur. The consequences of these failures and the likelihood of future failure do not show an improving trend. Those owners, operators, engineers, regulators and reviewers tasked with the responsibility of monitoring, surveillance and review of tailings dam integrity can benefit from the introduction of alternative tools for tracking dam safety: the use of leading rather than lagging indicators of dam integrity. Alternatively, is it possible to predict failure, rather than waiting for it to happen? Could we be more forward looking and anticipative in our vigilance, and if so how? This is particularly important for those structures where the risk profile increases with time. This paper proposes a shift in emphasis for tailings engineering practice to place more weight on leading indicators of dam structural integrity.

1 INTRODUCTION

Over the past four years three significant dam incidents have served to highlight new attention to dam integrity: the Mount Polley tailings breach on August 4, 2014 in British Columbia (Morgenstern et al, 2015); the failure of the Fundão tailings dam which resulted in the loss of 19 lives in Brazil on November 5, 2015 (Morgenstern et al, 2016); and the evacuation of nearly 200,000 people in response to a spillway failure of the largest water dam in the USA, Oroville Dam, California, in February 2017 (Wikipedia, 2017).

These incidents and other dam and tailings breaches have led to a substantial revision of legislation and regulation (such as in British Columbia, BC MEM 2017, 2016; EGBC, 2016a and in preparation in Alberta, Canada), and dam safety guidelines and bulletins, (CDA 2016, MAC 2017). Standards of leading practice in the design, construction and operation of tailings facilities have also improved. Increased attention and vigilance is being focused and there is no doubt that published standards of dam safety are rising.

However, despite the best efforts of the international tailings community, experience over the past decades and in the last five years in particular, has shown that tailings dam failures continue to occur. The consequences of these failures, and the likelihood of future failure do not show an improving trend – at least not sufficiently, or fast enough. Over the past 12 months we have witnessed two more dam failures involving fatalities in Mexico (Reuters, 2018 - La Cieneguita Mine tailings failure - 7 fatalities) and Kenya (CBC, 2018 - Patel water dam, Kenya - 47 fatalities).

This is not acceptable at a societal level and should not be acceptable within the engineering profession. Senior professionals must exert leadership to effect change.

2 WHY ARE FAILURES STILL OCCURRING?

Based on a reading of published accounts of recent failures and industry experience, the following factors appear to be relevant:

2.1 *Unregistered dams*

On May 9, 2018 an unregistered water dam in Kenya failed (CBC, 2018), with disastrous consequences. In all, 47 lives were lost. The tailings failure which occurred at Obed Coal Mine on October 31, 2013 (Wikipedia, 2018) was from an unregistered dam, from which 600,000 m^3 of coal tailings slurry entered the Athabasca river.

2.2 *Poorly informed dam owners and management*

As a result of concern about small dam owners and single dam owners in Canada, over the past year the presidential theme for the Canadian Dam Association has been to promote and broaden the awareness of dam safety and risks to all owners of dams. At the CDA annual conference in Kelowna, B.C. in October 2017, an entire parallel stream of conference technical sessions raised awareness among small dam owners and single dam owners.

2.3 *Insufficient professional engineering involvement*

The Merriespruit tailings failure in 1994 in South Africa (Wagener et al, 1997) led to the loss of 17 lives from a supposedly dormant tailings dam into which unsupervised tailings deposition had continued to occur. The dam was not licensed, not under the supervision of a professional engineer, and not actively monitored.

While the efforts of professional engineering institutions and regulators continue to raise standards in this regard, failures of dams with little or no engineering involvement continue to occur.

Leading jurisdictions now specify requisite levels of qualification for the Engineer of Record (EOR), Designer of Record (DOR) and other positions of dam safety leadership (Boswell and Martens, 2017).

2.4 *Absent or insufficient dam safety laws and regulations*

At the two-day workshop held in San Antonio, Texas in October 2017, “Lessons Learned from Recent Tailings Failures” convened by the US Society on Dams and the Association of State Dam Safety Officials (USSD, 2017), it was concluded that the regulation of tailings facilities across the USA was insufficient and inconsistent between states, and that more attention was needed in order to avert future tailings dam failures in the USA.

After the Mount Polley Failure, new legislation was introduced in British Columbia, (BC MEM 2017, 2016; EGBC, 2016a; MFLNRO, 2010) which in the opinion of the authors of this paper now represents the highest published standard of tailings dam regulation in current practice, worldwide.

In Alberta, Canada the existing Water Act is being strengthened in regard to dam safety (Boswell and Martens, 2017).

In the aftermath of the Merriespruit tailings breach in 1994, a South African mining guideline for mine waste disposal was substantially updated (Chamber of Mines, 1996), and a code of practice was introduced for tailings management (SABS, 1998).

However, many countries and regions continue to allow mining with insufficient regulation of tailings dam safety.

2.5 *Insufficient or untrained regulators and inspectors*

In Alberta it has now been recognized that inspection of dams with a higher safety consequence classification require more advanced skills of regulatory inspectors (Eaton, 2017). In particular, dams with a classification of High or more, as classified by the Canadian Dam Association

(CDA 2007, 2013), now require inspection by a professional engineer with relevant dam experience.

2.6 *A checklist-only approach to dam safety*

Cost pressures and over-competitive pricing of a dam safety review (DSR) may have the effect of consigning a DSR to the mere completion of a checklist. As a result, there appears to be an increasing demand for QA/QC procedures for dam integrity activities such as DSRs, dam safety inspections (DSIs), and annual performance reviews (APRs), to ensure that dam safety is actually assessed.

There is of course no substitute for professional engineers following the duty of care expected of them in the execution of their work in assessing dam safety and identifying and managing dam safety risks (Boswell and Sobkowicz, 2011).

2.7 *Rising risk profiles*

A significant distinguishing feature of tailings dams is that left unchecked, tailings dams, may be expected to follow a rising risk profile, since their construction continues over many years.

This characteristic hold implications for dam safety activities:

– Inspections and risk assessments such as Failure Modes and Effects Analysis (FMEA), should be regularly revisited upon any significant change in a structure, including moving from one phase of the project life cycle to another (from design, to construction, operation or closure).
– Operation, Maintenance and Surveillance (OMS) plans and actions must target active risks and credible failure modes.

2.8 *Lulled into instrumented apathy*

The mere existence of instrumentation such as vibrating wire piezometers, slope inclinometers and automated data loggers is no guarantee of dam safety. The safest dams are not necessarily those with the most number of instruments. Care should be taken to ensure that instruments continue to target actual risks and failure modes, that instruments are in working order, that engineers are still physically inspecting the structure, that the data and risks are being actively analyzed and interpreted and that corrective action is taken in a timely manner.

2.9 *Normalization of deviance*

Steven Vick has produced excellent work (Vick, 2017a, 2017b, 2014) which clearly demonstrates the consequences of the normalization of deviance for dam safety. Quoting from Vaughan (1996) in his paper Dam Safety Risk—From Deviance to Diligence (Vick, 2017a) used as his departure point the failure analysis for the Challenger Space Shuttle which exploded in January 1986, and which introduced the term normalization of deviance. The paper makes for fascinating but worrying reading. He further illustrates the folly of normalization of deviance with examples drawn from the tailings industry.

There were strong indications of the normalization of deviance in the months and years before the Fundão tailings failure – warning signals which should have been picked up from incidents and events in the years before, which contributed to the failure (Morgenstern, 2016). The same normalization of deviance applied to Mount Polley (Morgenstern, 2015), Merriespruit (Wagener et al, 1997) and many others. Hindsight of course provides a much clearer view than foresight, but recent lessons should not be ignored.

2.10 *Normalization of imponderable consequences*

Overarching all of the above factors is the deep understanding, at the conceptual stages of a proposed project, of the “what if” consequences of failure. What if the steep valley below the Stava dam became densely populated? What if a planned mining village was relocated to the toe of the Merriespruit dam?

At this Colorado based conference two years ago, Boswell and Sobkowicz (2016) argued that structures with extremely high i.e., imponderable consequences of failure should simply be avoided – that no low level of probability could reduce the risk to an acceptable level. In other words, in the event that a catastrophic tailings failure would lead to imponderable consequences, then no matter how infinitesimal the likelihood was calculated to be, the level of risk would be unacceptable, and the design should be reconceived to avoid the consequence altogether.

At Tailings and Mine Waste 2015 in Vancouver, the same authors (Boswell and Sobkowicz 2015), warned three weeks before the Samarco tailings failure that: "*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*."

3 LEADING INDICATORS

In the light of ongoing failures described above, and notwithstanding the increase in published standards and attention, what more could be done?

3.1 *Looking forward rather than backward*

Those owners, operators, engineers, regulators and reviewers tasked with the responsibility of monitoring, surveillance and review of tailings dam integrity may benefit from the introduction of alternative tools for not just tracking dam safety, but actually predicting it: the use of leading rather than lagging indicators of dam integrity. Is it possible to predict failure, rather than waiting for it to happen? Could we be more forward looking and anticipative in our vigilance, and if so how? This is particularly important for those structures where the risk profile increases with time (usually a result of increases in height of tailings facilities and contained volume of tailings and fluid and/or ageing of dams). This paper suggests a revised vigilance through focusing on leading indicators of dam integrity.

3.2 *A definition*

What are leading indicators, and how do they differ from lagging indicators?

Van der Poel (2012) has described the difference between leading and lagging indicators in performance management as follows:

"In performance management we often talk about "lagging" and "leading" indicators. But what do they mean exactly?

Lagging indicators are typically "output" oriented, easy to measure but hard to improve or influence while leading indicators are typically input oriented, hard to measure and easy to influence.

Let me illustrate this with a simple example: For many of us a personal goal is weight loss. A clear lagging indicator that is easy to measure. You step on a scale and you have your answer. But how do you actually reach your goal? For weight loss there are 2 "leading" indicators: 1. Calories taken in and 2. Calories burned. These 2 indicators are easy to influence but very hard to measure. When you order lunch in a restaurant the number of calories is not listed on the menu. And if you are me, you have no clue how many calories you burn on a given day."

Similarly, in tailings failure analysis, tracking fatalities per year or millions of cubic metres of escaped tailings slurry may be straightforward, but these lagging indicators are unhelpful in improving future performance. They are simply reminders of underperformance.

What are some of the key indicators which are able to give advance warning of risk – that we might describe as leading indicators, rather than lagging indicators?

4 STRUCTURAL PERFORMANCE INDICATORS

There are many leading indicators of good performance which provide assurance of sound tailings disposal practice. Some of the general indicators are summarized in Sections 5 below.

However, the focus of this paper is centered on the performance indicators which may be described as structural. These leading indicators of sound structural performance are described in the section immediately below.

4.1 *Leading indicators which forewarned of catastrophe*

Several good lists of tailings failures are described in other papers and websites as included in the references to this paper, but are not reproduced in further detail here. This paper considers many of the failures which have taken place over the past 50 years, and selects seven published examples:

- Buffalo Creek, 1972 (Blight and Fourie, 2003).
- Bafokeng, 1974 (Blight and Fourie, 2003).
- Stava, 1985 (Morgenstern, 2000).
- Merriespruit, 1994 (Wagener, Craig, Blight and Strydom, 1997).
- Los Frailes, 1998 (Alonso and Gens, 2006).
- Mount Polley, 2014 (Morgenstern et al, 2015).
- Samarco, 2015 (Morgenstern et al, 2016).

These well documented tailings failures show how certain leading indicators point specific attention, warning of impending catastrophe.

From these papers, a list of key leading indicators was drawn up, and referenced back to the examples, in Table 1 below. Clearly there could be many more indicators selected (and some are further listed in Section 5 below), but in the authors' view these were the most reliable structural indicators of tailings dam risk.

Table 1. Leading indicators of impending failure.

Historical Tailings Failure, Date / Reference	Buffalo Creek, 1972 Blight et al ('03)	Bafokeng, 1974 Blight et al ('03)	Stava, 1985 Morgenstem (2000)	Merriespruit, 1994 Wagener et al ('97)	Los Frailes, 1998 Alonso & Gens ('06)	Mt. Polley, 2014 Morgenstem et al('15)	Samarco, 2015 Morgenstem et al('16)
Leading Indicator							
Rate of rise	×		×	×	×	×	×
Beach freeboard	×	×	×	×	×	×	×
Height of dam	×	×	×	×	×	×	×
Contained volume of fluid	×	×	×	×	×	×	×
Changes in water level	×	×	×	×	×	×	×
Slope steepening		×			×	×	
Recycle water capacity	×	×	×	×	×	×	×
Foundation geotechnics					×	×	

As illustrated in the demarcated cells above, it is interesting to note just how many of the leading indicators were present just before each of the failures occurred. Each of the leading indicators is discussed in detail in the following sub-sections.

4.2 *Rate of rise*

In the authors' experience, the measurement of rate of rise has been used as a benchmark indicator for tailings dam performance for at least 50 years. However, our experience as an industry over the past 50 years has also continued to demonstrate through failure upon failure, the belief that some operators hold that somehow, they might be immune to the risk of excessive rates of rise - until it actually happens to them, of course.

Morgenstern et al (2016) describe very high incremental monthly and annualized rates of rise that immediately preceded the Fundão tailings failure, in some cases up to an annualized rate of rise of 35 metres per year (Figure 1). It is no coincidence that upon breaching, the entire contents of the Fundão tailings facility were lost, a most unusual tailings failure characteristic.

Pollock, Mettananda and MacGowan (2014) show that oil sands tailings beach above water (BAW) deposition at annual rates of rise in excess of 10 metres per year, which is not track-packed, is liquefiable.

One of the authors of this paper showed in a series of papers at T&MW conferences (Boswell, 2009, 2011, 2015, 2017) the benefits which accrue from consistent adherence to rate of rise controls and limits in tailings deposition practice. Advice included the following:

- Calculation of allowable rates of rise for each deposit and each material.
- Establishment of allowable limits for rate of rise, and maximum height, based on the dewatering and consolidation characteristics of the tailings material.
- Measurement of incremental and average rates of rise.
- Strict compliance with seasonal, annual and overall rate of rise limitations.
- Adjustment of trigger levels and limits to cater for unseasonal or extreme precipitation.

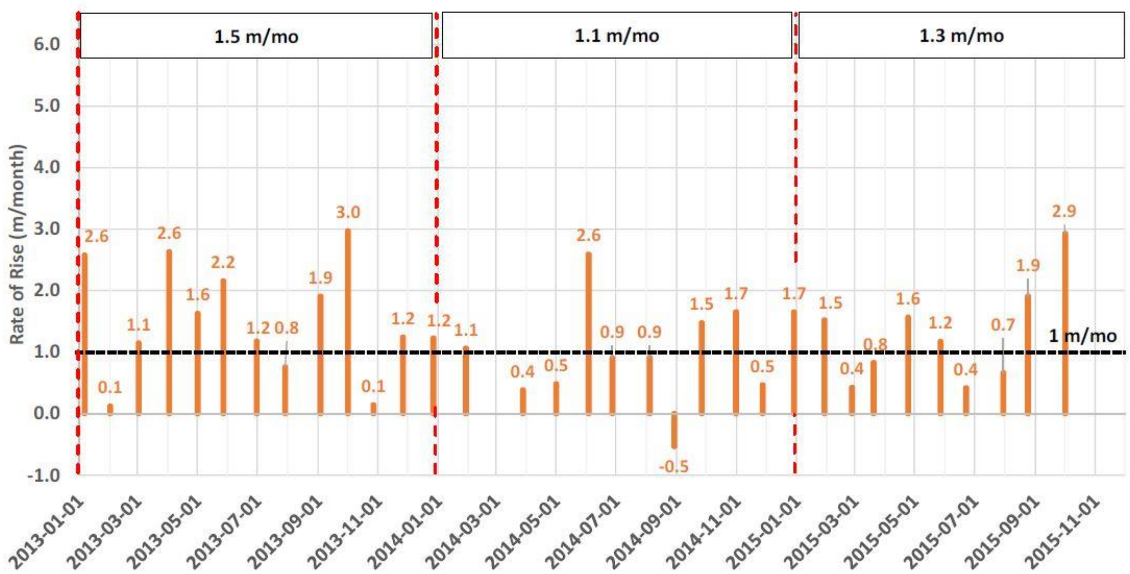

Figure 1. Rate of dam crest rise at Fundão left abutment setback (from page 49, Morgenstern et al, 2016)

4.3 *Beach freeboard*

A distinction should be made at the outset, between total freeboard and beach freeboard. As the name implies, beach freeboard is the amount of freeboard provided by the beach alone.

As illustrated in Figure 2, total freeboard provides the (as-measured) overall defense against overtopping, and may be rapidly improved by elevating the crest of the dam. Beach freeboard is much harder won but provides a number of additional benefits:

4.3.1 *An additional defense against liquefaction*

Tailings deposited on a subaerial beach, or beach above water (BAW), is usually not liquefiable, whereas tailings deposited sub-aqueously or beach below water (BBW) is usually liquefiable. There are exceptions to this rule, depending on climate, mineral type, particle size distribution, slurry specific gravity, mechanical compaction, but the trend is valid.

4.3.2 *Improved slope stability*

Existence of a long beach provides greater separation between the outer embankment and the pond, and consequently improved control of phreatic surface within the tailings and resulting embankment slope stability.

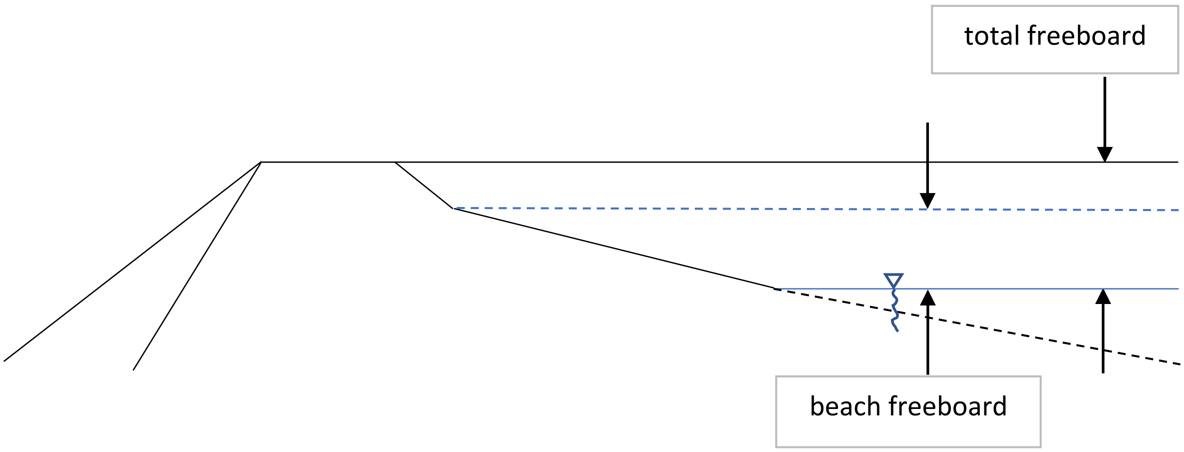

Figure 2. An illustration of the meaning of beach freeboard (vertical scale exaggerated)

4.3.3 *Better pond control*

A long beach also provides better pond control through the establishment of improved deposition basin geometry. In one of the author's experience, on one large platinum tailings dam, beach freeboard of over 15 metres in vertical height was achieved, providing substantial margins of safety against overtopping, flooding, pore pressure rise and slope instability.

The clearest illustration of the value of beach freeboard in defense against catastrophic failure, may be found in a photograph of the Cadia tailings failure (Cadia, 2018) in Australia, in May of this year, shown in Figure 3 below.

Figure 3. Slope failure in upper compartment at Cadia, Australia (Cadia press release, 2018)

Without the added protection of the significant beach freeboard shown in the photograph, the local slope failure shown in the upper compartment would not have been contained, but instead would likely have become a catastrophic tailings flow failure, cascading into the lower compartment and adding to the flow volume with multiplied severity of downstream consequences.

4.4 *Height of dam*

Robertson (2011) argued that tailings dam risk is very closely tied to absolute height of the structure. He also presented a thought provoking case for the rising risk profile of dam designs over the last decades. It is difficult to disagree with him.

He advanced an argument as shown below.

"Each 1/3 century:

Volume of waste increases by ~10 fold
Area of waste increases by ~ 5 fold
Heights of dams/dumps increase by ~ 2 fold

Max. Dam heights in1900 ~ 15 m
Max. Dam heights in 1930's ~ 60 m
Max. Dam heights in 1960's ~ 120 m
Max. Dam heights in 2000's ~ 240 m
Max. Dam heights in 2030's ~ 480 m

Risk = Likelihood x Consequences
For dams: Likelihood ~ 'somewhat' proportional to height
Consequences ~ 'somewhat' proportional to volume
Increase in 'potential risk' per 1/3 century is ~ 2 X 10 = 20 fold"

Existing mine and tailings planning, design and risk management tools are demonstrably capable of taking these factors into account in order to manage risk proactively.

However, as noted in Section 2.10, the authors of this paper have argued that tailings dams which present imponderable risks to society should be reconceived (Boswell and Sobkowicz, 2015; 2016).

4.5 *Contained volume of fluid and liquefiable material*

While Robertson (2011) proposed that absolute volume of contained waste is an indicator of risk, there may be a better leading indicator. An extremely large dam like that at Chuquicamata Copper Mine in northern Chile now contains well over 1 billion m^3 of tailings and covers 52 km^2 (Vogt, 2006), but the tailings are safely contained.

A better indicator of risk would be volume of fluid and liquefiable (by static or seismic means) material. An increasing trend in contained liquid volume is a reliable indicator of rising risk profile and should trigger additional precautions, in order to be safely managed.

Without the fluid and liquefiable material contained within the tailings dams, the catastrophic failures referred to in this paper would not have occurred.

Contained volume of fluid and liquefiable material is thus a reliable leading indicator.

4.6 *Changes in water levels*

Changes in supernatant water levels, in groundwater levels or within the phreatic surface of a tailings dam are usually very good indicators of reducing stability and/or increasingly severe consequences of failure.

Leading industry practice has employed piezometers and other instrumentation for many decades, for good reason. However, the mere existence of instrumentation is no guarantee of dam safety, as cautioned earlier in section 2.8 above.

4.7 *Slope steepening*

Many tailings failures have been preceded by the steepening of embankment side slopes: Mount Polley (Morgenstern et al, 2015), Los Frailes (Alonso and Gens, 2006) and Bafokeng (Blight and Fourie, 2003) are well published examples.

Slope steepening is often a desperate remedial measure, sometimes introduced to contain increasingly large amounts of fluid and to maintain sufficient freeboard. It is a poor choice of defense, often proved so with disastrous results, as shown in the references immediately above.

The use of beach freeboard as described in section 4.2 while not a quick fix by any manner of means, is a far more reliable remedy for freeboard problems. Sufficient capacity in recycle water storage is also a sound defense (Section 4.8 below).

4.8 *Recycle water capacity*

Catastrophic tailings failure is seldom possible without the presence of water or fluid. By the same token, the maintenance of a “zero pond” hydraulic fill dam is not achievable without the provision of adequate recycle water capacity, in a separate water dam.

Many large valley fill dams hold very large quantities of supernatant and precipitation. This is an ongoing risk which demands very close attention.

Reduced capacity for recycle water or water containment, or rising water inventories are usually reliable indicators of risk. This is especially true for poorly managed or unmonitored facilities, such as the Merriespruit failure (Wagener et al, 1997).

4.9 *Foundation geotechnics*

The Los Frailes failure in 1998 (Alonso and Gens, 2006) was a clear message to the international tailings community of the importance of deep seated weak foundation layers and how they could contribute to catastrophe.

However, no-one really took any notice, until 16 years later an almost identical failure mechanism caused the Mount Polley failure in 2014 (Morgenstern et al, 2015). This failure introduced widespread awareness of the risks of deep seated weak clay layers, the importance of understanding of the engineering geology of the region, and the importance of sufficient geotechnical investigation.

Soon after the Mount Polley failure, the BC government immediately addressed letters to every owner of a tailings dam, whether operational or not in BC, demanding immediate confirmation of the existence of (and appropriate consideration of) weak clay foundation layers below tailings dams. Similar letters were addressed to other dam owners by regulators elsewhere in Canada.

Engineers and Geoscientists BC (EGBC, formerly APEGBC) published a useful technical guideline in 2016 entitled Site Characterization for Dam Foundations in BC (EGBC, 2016b). This document provides substantial and detailed requirements for consideration of dam foundation geotechnics.

5 GENERAL LEADING INDICATORS

Time and space does not allow for further detailed consideration in this paper of other leading indicators which although not necessarily structural in nature, are nevertheless most useful in identifying and managing dam safety risks.

5.1 *Human performance indicators*

These include:

- Management commitment to dam integrity.
- Dam safety leadership.

– Documented roles and responsibilities for Engineer of Record (EOR) and Designer of Record (DOR).
– Up to date OMS, EPP and ERP manuals.
– Documented procedures for design changes, including “management of change”.
– Key staff turnover.
– Changes in contractor or operator.

There is an excellent recent publication, Guide to the Management of Tailings Facilities Third Edition, by the Mining Association of Canada (MAC, 2017), which is essential reading in this regard, compliance with which is in any case required for any member of MAC. The guide itemizes system essentials and organizational requirements for a sound tailings management team.

Boswell and Martens (2017) summarize the roles and responsibilities required of all personnel associated with dam safety, including the EOR and DOR. In addition, there has been work in the USA in 2017 and 2018 on a document by the GBA entitled Tailings Engineer of Record Task Force (GBA, 2017). This is intended to be a US National Practice Guideline for the Tailings Storage Facility (TSF) Engineer of Record, but has not been published yet.

5.2 *Other leading indicators*

These include:

– Mine profitability.
– Commodity price.
– Changes in production and storage capacities.
– Changes in the regulatory domain.
– Changes in environmental milieu.
– Stakeholder influences and changes.

Davies and Martin (2011) provide thought provoking insight into the direct correlation between adverse commodity price cycles and tailings dam failures.

6 CONCLUSION

For every failed tailings dam, there exists a large number of stable, well managed tailings facilities around the world. These structures do not achieve stability by chance, coincidence or serendipity. Their stability is the result of sustained effort over many years by the engineers that design and build them.

Nevertheless, there is an unacceptable rate of failure of tailings dams, worldwide and in our own countries. Many of these failures occurred under the watch of reputable engineers and consultants, working for responsible dam owners. A step-change improvement in engineering practice is urgently needed.

This paper outlines one path forward: placing more weight on leading indicators of dam structural integrity. It is hoped that the ideas herein will initiate a conversation in the dam engineering community and an evolution in dam engineering practice.

We have the ability to enact appropriate regulations. We also have the tools and the expertise to manage dams safely. However, if we do not engage top management in a culture of integrity management then we will continue to have failures like the ones we have seen.

We have to have the will to effect change. Senior professionals must exert leadership to effect this change.

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Useful websites re tailings failures:

http://www.tailings.info/casestudies

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

http://www.wise-uranium.org

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