Tailings impoundment failures, black swans, incident avoidance, and checklists

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ABSTRACT: The thesis of this paper is that tailings impoundments fail as a result of a string of incidents, each of which is trivial and within the bounds of normal events, but which, taken together, constitute an event so unusual that it lies outside of the bound of normal occurrence and experience. The string of incidents leading to the failure of a tailings impoundment may be understood and evaluated in the light of the theory of the Black Swan, an event that nobody could have foreseen, that results in extreme consequences, and which can be explained after its occurrence by all on the basis of standard knowledge. In this paper we examine current theories and hence methods for avoiding failure of tailings impoundments. We find them all lacking, and so we proceed to set out proposed approaches based on incident control, checklists, and Black Swan avoidance to limit and hopefully eliminate the possibility of failure of tailings dams and the consequent loss of life and property.

1 INTRODUCTION

This paper is about the philosophy of slimes dam failures. You can call them tailings impoundments, processed material containment facilities, storage locations, or mine geowaste areas. The fact remains they are dams that contain slime—thus we prefer the name we grew up with and which we still think is accurate and descriptive.

You may blame the senior author for the opinions in this paper. You must thank the junior author for checking the facts and having the courage to be associated with our ideas.

We seek to get to the bottom of an every-pressing issue: why do slimes dams fail? Some attribute failure to engineering issues; some attribute failure to institutional practices; some blame the designer or the mine. A favorite reason is Acts-of-God, most often extreme precipitation. The best theory we know of attributes accidents to a failure to control incidents; the idea is that ten unattended incidents equal one accident; ten accidents equal one fatality. We believe this is the root cause; and if not the cause, at least the best way to proceed to eliminate the failure of slimes dams and the attendant deaths.

We are fascinated by the theory of the so-called Black Swan; the idea that some things are so unusual that nobody can foresee their occurrence, although after the event everybody can explain why the event occurred. Thus we examine the role of Black Swans in causing slimes dam failures and suggest practical ways to hunt and kill Black Swans before they come to kill you by failing your slimes dams

2 THE BLACK SWAN

After the economic collapse in late 2008, many sought the fundamental reasons for the economic collapse. Before the collapse, nobody saw it coming—although some may claim they did, we have seen no convincing evidence of anybody predicting its occurrence. The event had an extreme impact; economic edifices came crashing down and many lost their houses, their investments, and their jobs.

After the collapse, we find it very simple to explain why it happened: the collapse is the result of the granting of mortgages to people who did not have the ability to pay. We all know somebody who kept buying a bigger and bigger house costing many multiples of their annual salary. We all know people who kept taking bigger and bigger loans against their house for foreign travel, a new car, more clothes, or just more plastic or exercise equipment to clutter the garage.

Some ascribe the collapse to the imprudence of banks and finance houses who bundled bad mortgages into packages to be sold to distant investors rendered incautious by near-dishonest ratings firms. Behind it all there appears to have been a battalion of overly trained mathematicians armed with flawed theories of statistics; specifically statistics that said that there was so vanishingly slim a chance of the mortgages going sour that reasonable people need not be concerned. This was topped by inattentive managers who seemingly did not know or understand what their underlings were doing

In the book, *The Black Swan – The Impact of the Highly Improbable* by Nassim Nicholas Taleb, the author notes three characteristics of a Black Swan:

- It is an outlier, as it lies outside the realm of regular expectation, because nothing in the past can convincingly point to its possibility.
- It carries an extreme impact.
- In spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable.

Let us explore the thesis that tailings impoundment failures are generally Black Swan events in that nothing in the past convincingly points to their occurrence, that they have an extreme impact, and that after the failure, human natures makes the even explainable and predictable.

3 BAFOKENG

We have previously written about the failure in 1974 of the Impala Mine, Bafokeng slimes dam that killed thirteen and cost millions to clean up. This is what we wrote:

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.

Geoff Blight in his new book writes in detail about possible failure causes. He is forced to conclude: "It appears at first sight that the dyke did not fail by conventional overtopping. Eyewitness accounts all point to a failure by piping erosion. However, a satisfactory explanation of how the initial hole formed in the wall was never reached."

Professor Jennings, for whom I worked to collect the data to evaluate the failure, was convinced that piping began between two layers of low permeability slime bordering a zone of higher permeability sand tailings. Such zones existed, as I saw too often climbing over the failure zone to measure things.

Personally I think it is easy: to pinpoint the root cause of the failure of the Bafokeng dam. Nobody could or did foresee the Black Swan. Those who ran the mine and who operated the impoundment saw no reason for concern. They had no concept that the dam could or would fail—nothing in the past pointed to such a failure, and nothing pointed convincingly to the possibility of such a failure. But the failure occurred, and the failure had great impact.

Now it is clear: the pool was too close to the perimeter dikes, it was raining hard, there was seepage flow in saturated sand layers between clay layers, and the bulldozer operator induced liquefaction in the confined sand layer. Thirteen died. Now we know we must avoid all these factors.

In the years following the failure, the senior author evaluated two more platinum slimes dams that failed. The causes of failure, as at Bafokeng, included a pool too close to the perimeter dikes and high pore pressures in the outer shell. In addition, it was clear that there was slope failure caused by sliding along the weak clays that are found throughout the mining district. If you consider that at that time, there were no more than about ten platinum tailings impoundments in the area, the probability of failure works out to almost 33 percent.

Some changes were made to the standards of practice in the wake of these three failures, but they were insufficient to preclude the Merrispruit failure which we now consider.

4 MERRIESPRUIT

Geoff Blight has this to say about the failure of the Merrispruit slimes dam in 1994;

"On the night of February 22, 1994, a 31-m high dyke upslope of the village of Merrispruit, South Africa, failed with disastrous consequences. The dyke breached a few hours after 30 to 55 mm of rain fell in approximately 30 minutes during a late afternoon thunder storm. The failure resulted in some 600,000 cubic meters of liquefied tailings flowing through the town causing the death of 17 people."

Wikipedia records this—and it sound like the person writing knew what actually happened;

"In March 1993 an inspection noticed seepage along the north wall and it was agreed to stop deposition into compartment 4A. According to the contractor, the freeboard at this time was an acceptable 1.0+ m. The division of compartments 4A and 4B was breached some time before the disaster, resulting in drainage from 4B to 4A. The extra drainage led to a freeboard of 300 mm. Despite the termination of daywall construction, excess plant water containing tailings continued to be deposited, with the water decanted by the penstock and the remaining tailings using up the remaining freeboard."

One of the authors has chatted informally with some of those who were involved in examining the area after the failure. They all acknowledged that the mining company had cut to the bone to reduce costs and as a result the dam was neglected, competent people were not involved, and the contractor's staff were overly confident (to the point of negligence) of their abilities. Undoubtedly there was institutional inertia and over-confidence based on past successes—or at least an absence of past failure of similar structures in the area. Regulations were in place, but they were inadequate, not followed, and not enforced. Everybody involved, from top to bottom of the chain of command and responsibility, failed to foresee the event which we must conclude lay outside the realm of regular expectation, because nothing in the past convincingly pointed to its possibility.

The failure had an extreme impact. In spite of its outlier status, soon after the event almost everybody involved was able to concoct explanations for its occurrence and render the failure explainable and predictable. As Blight points out: "Everybody was to blame and everybody blamed somebody else and nobody was held responsible. And the man on the ground at the slimes dam did not conceive of another big storm and what it could, and did do."

5 INCIDENT CONTROL

On the basis of but these two spectacular slimes dam failures, we submit that they were indeed manifestations of the arrival of a Black Swan. We believe the Black Swan was able to come and wreak havoc because of the failure by too many people to control the little incidents that if attended to would have blocked the path of an oncoming bird of doom.

We need hardly expound on the theory of incident control here. It is well documented in the literature and in countless sites on the web. Suffice to say that the essence of incident control is that if you control the little things, the big things do not happen. As we said in the introduction, ten unattended incidents equal one accident; ten accidents equal one fatality.

One story to illustrate. Many years ago the senior author was digging and profiling test pits in the cover of a steep (1.4 horizontal to 1.0 vertical) and high (100 m) side of a landfill perched above the I60 Freeway leading east from Los Angeles. A clod from the pile of soil dug to make the test pit rolled down the slope, jumped the fence, and hit a passing car, causing a big mud splat on the door. The driver continued home—we never heard from him.

The company for which the senior author worked had in place an Incident Control Program. So he reported the incident. The result was a long and high metal and plywood safety fence along the perimeter of the landfill. We proceeded to strip the cover and replace it with a geogrid reinforced cover. We did over $100 million of work and there were no serious injuries and no fatalities. I believe the Incident Control Program is to be credited with this success.

We are not aware of any mine that has in place a Tailings Storage Facility Incident Control Program. No wonder failures occur and will occur.

6 FAILURE CAUSES

The literature and the web are replete with records of slimes dam failures. Common postulated technical causes of failure include: earthquakes, foundation and/or slope failure, overtopping during heavy rains, washout pursuant to pipe failures, and piping resulting from the pool being too close to the perimeter dikes.

Some proceed to blame non-technical factors for slimes dam failures. They say root causes include:

- Institutional, including cultural and stakeholder attitudes and practices that fail to be aware or concerned about the presence and/or condition of the tailings impoundment.
- Management, including the absence of knowledgeable managers and/or the failure of those with the power and responsibility to do so to act.
- Regulatory, including an absence of or inadequate regulations, and/or a failure of those charged with doing so to enforce existing regulations.

We submit these are but sources of incidents. We concur that, as at Merrispruit and Bafokeng, there were indeed serious and systematic institutional, management, and regulatory lapses. Each and every one gave rise to an "incident" that if eliminated would have blocked the path of the deadly Black Swan.

7 OTHER POSTULATED REASONS FOR FAILURES

An early paper by Edwin Smith (1973) notes that "according to mining folklore, no tailings dam has ever been completed without at least one failure occurring during the deposition of the particles." He lists these causes of failure: foundation failure; slope failure; overtopping by flood waters; erosion of face; piping; collapse of dewatering conduit; and liquefaction. He recommends the application of the Observational Method as the best way to build tailings impoundments and keep them safe.

Over the years, papers in previous Tailings and Mine Waste Conferences have sought to pinpoint the cause of failure. The most dramatic assignation of responsibility is in the 2003 proceedings where Allen Gipson blames "owners, engineers, designers, and operators [who] are not performing their work in accordance with the standards of practice that should be followed." There is not much more to say in the face of such an assertion.

Steven G. Vick (2002) also examines reasons for failure of mine geowaste facilities. In his magnificent book he explores the role of subjective probability and engineering judgment. His book is so profound that we do no more than note it here and maintain that anybody charged with keeping mine geowaste facilities safe must read it.

Michael Davies and Todd Martin (2009) present a tantalizing institutional reason for the failure of tailings dams. They examined the timing of cycles of boom and bust in the mining industry and the timing of failures. They conclude that between one and two years after a period of depressed mining activity (poor economic conditions), there is likely to be a slimes dam failure. They ascribe this to the possibility that during poor economic times, mine management cuts back on the costs of managing and operating the tailings facilities and inevitably this leads

to a failure. They provide some plausible reasons why the tailings dam could fail after the economic boom:

- Permit haste
- Fast track investigation, design, and construction
- Cost cutting after the boom
- Inexperienced but overconfident designers
- Lack of independent third party peer review
- Rapid turnover of mine personnel
- Disconnect between design expectations and operational reality
- Development of deposits that have been left undeveloped for good reason
- "Cookie cutter" designs.

We are not aware of any evidence that the managers ultimately responsible for the failure of the Bafokeng dam had cut back in any way preceding the failure. In fact, the construction company operating the dam on behalf of the mine had, some time before the failure, employed their first qualified civil engineer in an attempt to improve the standard of their service to the mining industry.

In the case of the Merrispruit failure, there are hints that management had cut back on provision of services related to operation and oversight of the dam. But the slimes dam had always been operated that way and there was no valid reason to believe it would act any differently in the future.

8 HOW TO AVOID FAILURES OR AVOIDING THE BLACK SWAN

Let us proceed to examine what can be done to stop the Black Swan from coming to induce failure of slimes dams. Of course the easy answer is: control incidents. We recognize, however, that this implies positive action. Thus we take a more detailed look at what individuals, companies, and society as a whole can do to augment a good Incident Control Program.

Taleb says this about incorporating Black Swan thinking into your life: "I am very aggressive when I can gain exposure to positive Black Swans—when a failure would be of small moment--and very conservative when I am under threat from a negative Black Swan. I am aggressive when an error in a model can benefit me, and paranoid when an error can hurt. This may not be interesting except that it is exactly what other people do not do. In finance, for instance, people use flimsy theories to manage their risks, and put wild ideas under "rational" scrutiny."

Clearly the individual charged with some aspect of a slimes dam can hunt the Black Swan by acting as Taleb does. But this takes a bold, confident, and knowledgeable professional. Too often, cultural, societal, and even professional practice precludes prudent, individual action that amounts to Black Swan hunting. In the case of a heap leach pad failure of which we are aware, professional individuals were pressured to perform fast, were greedy to profit by fast performance, and fell into the trap of relying on statements by others instead of undertaking the evaluations themselves. They were too proud to consult with peers or submit to review. Now the lawyers are on their tail and the country is saddled with a mining mess.

Many, but by no means all, mining companies have taken many steps to prevent a recurrence of past tailings dam failures. These include:

- Employ experienced professional staff. This is a problem in most times as the perpetual calling by head-hunters attests.
- Engage reputable consultants. Most consultants are reputable, but most are also susceptible to lapses if improperly managed and controlled.
- Demand conservative engineering. This is good to do, but nearly impossible if the accountants have any sway and the project manager is profit and bonus motivated.
- Inspections by regulators. As we write, the US eastern coal mining industry is under a cloud as a result of a mine accident that killed nearly thirty miners. It appears as thought the regulations were in place, the inspections were being made by the regulators, and the technology existed to preclude the accident. The sad fact, however, is that the mine in question had been inspected the very morning of the accident. The inspector, the miners, and management failed to conceive of the accident that did occur. It

was outside of their field of imagining, although once all the causes are established, it will seem obvious that they should have known.

- More conservative engineering designs. We note our perennial favorite, namely the UMTRA Project where we had to design in accordance with U.S. Federal law for a period of stability of 1,000 years. Thus we designed for the maximum probable precipitation, the maximum credible earthquake, and so on. It can be done as a way to avoid both short-term and long-term Black Swans, but how many societies have the courage or check-book to demand this of their mines?

9 SUGGESTED APPROACH

We suggest the following as the set of actions that should be undertaken if you are an individual, a consultant, or a mining company charged with the safety of a tailings impoundment and you wish to go Black Swan hunting:

- Use the Wisdom of the Group. There are many ways to capture the wisdom of the group—as good a way as we know of to identify potential Black Swans. Some people call the process risk assessment, but there are many ways of facilitating wise thinking, including: Risk Assessment; Failure Modes and Effect Analysis; Value Engineering; and Multi Accounts Analysis. The senior author personally prefers the FMEA approach although he has participated in many other sessions adopting variants, and they mostly worked.
- Prepare a Risk Assessment Report and Monitoring Plan. The overall objective of using the wisdom of the group is to compile a Risk Assessment that is used as the basis of a Monitoring Plan. In other words for each identified risk of malfunction or failure, put in place an observation routine (visual and/or instruments) so that you get early warning of potential impending malfunction and/or failure. Then compile, as we note below, an Observational Method Plan that provides predetermined courses of action as practical responses to observed (monitored) performance or deviation from anticipated performance.
- Compile an Observational Method Plan. The Observational Method is well-known in geotechnical engineering, so we say no more about the method here other than that it forces you to establish logical monitoring and observation routines, to identify what may go wrong, and to establish before you start what you are going to do if things start to go wrong. The Observational Method, correctly applied, is no more than the construction of look-out forts, their consistent manning, keeping a look out for an oncoming Black Swan, and the preparation of an arsenal of weapons to slay the swan as it glides to your project and discredit.
- Implement an Incident Control Program. We know of no tailings facility that is part of an Incident Control Program. It is a nuisance and sometimes offends the powers that be. Yet we submit that a comprehensive Incident Control Program will nip in the bud most things that have ultimately lead to slimes dam failures.
- Compile Checklists of what to do when designing, constructing and operating a tailings facility, and focus on what to do when things start going wrong. Note the book by Atul Gawande who proposes that proper use of checklists can improve the practice of medicine and the safety of airplanes. There are many checklists for tailings impoundments built into the many documents put out by national organizations. One that violates all the recommendations for a good checklist is from the Mining Association of Canada (1998). We suspect none of them takes a "kill the Black Swan" perspective. We submit that all are probably too unconservative. In particular, avoid any that have sustainable in the title, for by definition this means they avoid the truth, or have been written by consultants trying to make it easier for cash-strapped clients. They obviously need to be re-written to be more outlier-event averse, but that is no good reason not to start now.
- Ensure Regular Peer Review. Peer reviewers are easy to fool and mislead. Peer reviewers are as susceptible as any group to herd-thinking, and blindly following the lead of one dominant individual who does not fall asleep in peer review meetings. Never-

theless, if carefully chosen they are at least independent, force the designers and operators to prepare presentations and argue their case (probably the greatest benefit of the whole process), and they may just notice something management is too busy to attend to.

10 CONCLUDING THOUGHTS

In this paper, we reject simplistic explanations of slimes dam failures predicated on economic cycles, heavy rains, piping, management inattention, regulator incompetence, and so on. We submit that every slimes dam failure can be traced to a string of events (positive incidents or failure-to-act incidents), that in concert or in sequence are the cause of the failure and the attendant deaths.

We submit that the immediate causes of most slimes dam failures are such that the failure could have been predicted and/or precluded by application of standard engineering practices and techniques of the time. It would be fair to say that at the time of the Bafokeng failure, the engineering knowledge and techniques were in place to predict failure, if an engineering examination had been undertaken. Without doubt, at the time of the Merrispruit failure, the engineering knowledge existed; had it had been brought to bear, failure would not have occurred.

Thus it is not technology or a failure of technology that kills. Lives are lost when a string of incidents occurs, each in itself relatively trivial, but in concert, deadly. The answer is simple: control the incidents, technical, engineering, and institutional. It is the graffiti theory: control the graffiti and you reduce crime.

In this paper, we recommend that for every slimes dam/tailings facility/processed material containment area there should be:

- Regular facilitated wide person deliberations to think things through
- Regular peer review to put the spotlight on practices, good and bad.
- A comprehensive Risk Assessment to establish the things that could go wrong and to form the basis of the instrumentation and monitoring plan, to be implemented in conjunction with an Observational Method Plan.
- An Observational Method Plan, to guide the monitoring and associated actions
- An Incident Management Plan, to enable you to deal proactively with the little things that if left unattended will combine to enable the Black Swan to triumph.
- Simple Checklists on what to do when things start to go wrong.

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