The History of Risk Assessment of Tailings Facilities

Jack Caldwell
Robertson Geoconsultants, Vancouver, BC, Canada

ABSTRACT

Terzaghi, Peck, and Cassagrade wrote from the 1950s onward about risk assessment of water dams and embankments. Their scepticism of the methods probably delayed use of risk assessment of tailings facilities for decades. The first paper on risk assessment of tailings facilities was in 1978 by Oskar Steffen. What he recommended then is as relevant today as it was then—and equally as ignored now as it was then. Over the years the methods of risk assessment were refined in the context of water dams and mine open pit slopes. But little happened in the tailings field. In the early 2000 there were a few pioneering papers on risk assessment of tailings facilities. But they were so detailed and of little practical application that they too were ignored. Canadian and Australian guidelines for tailings facility design and operation begun from 2000 onwards to call for the application of risk assessment in the tailings facility field—but few followed the guidelines. In 2005 a PhD thesis re-examined the 1974 failure of the Bafokeng tailings facility using risk assessment methods. But papers based on the thesis were not published. Then Mt Polley failed. The British Columbia Ministry of Energy and Mine found in their report issued in late 2015 that the mine manager had failed to apply relevant Mining Association of Canada guidelines that call for tailings facility risk assessment. They concluded the failure may not have occurred had the manager undertaken or considered risk assessments. In late 2015, the Samarco tailings facility failed. From what we read on the web, the design engineer intuited that things were unsafe—but he did nothing substantial. This paper concludes by examining what the Samarco engineers may have concluded had they just applied the basics of the Bafokeng risk assessment—and done what the BC Ministry of Energy and Mines said should have been done for Mt Polley.

1 INTRODUCTION

Risk assessment theory & tools are amongst the many that may be used by the tailings facility engineer in the design, operation, and closure of a tailings facility. Risk assessment will not solve the issues any more than a suite of computer codes. Risk assessment will, however, assist the tailings engineer in formulating the problems, focusing their attention, and exercising professional judgment.
Today risk assessment methods are well advanced, well documented, and ready to be used by anybody with the time, need, and interest. But most risk assessment literature focuses on topics other than tailings facilities. Accordingly, in this paper I seek to introduce the topic by examining the history of the application of risk assessment in tailings facilities. Sometimes I write of the engineers and their papers on the topic. Sometimes I write of the institutions that introduced and applied risk principles. For as is the case in the advance of any branch of science and engineering, the advances are the result of talented individuals and responsible institutions.

Hopefully this introductory history will prompt others to expand the use and benefits of risk assessment approaches to the goal of zero tailings facility failures. And if I have left out key people, important institutions, or seminal ideas and events, I trust that you will point this out to me, or write new papers on the topic.

Of course the idea of geotechnical risk as applied to large earth structures—and tailings facilities are surely amongst the largest of geotechnical structures—has been around a long time. In 1948 Terzaghi noted “in earthworks engineering the designer has to deal with bodies of earth with complex structure and the properties of the material may vary from point to point.” In the same year Donald Taylor wrote: “Two specimens of soil taken at points a few feet apart, even if from a soil stratum which would be described as relatively homogeneous, may have properties differing many fold.”

In 1964 Cassagrande defined “calculated risk” in geotechnical engineering thus:

(a) “The use of imperfect knowledge, guided by judgment and experience, to estimate the probable ranges for all pertinent quantities that enter into the solution of a problem.

(b) The decision on an appropriate margin of safety, or degree of risk, taking into consideration economic factors and the magnitude of losses that would result from failure.”

We will see these themes or ideas repeated as we follow the history of the development and application of risk to tailings facilities, namely:

- Imperfect knowledge
- Variable soils and tailings materials
- The need for judgment and experience
- Appropriate factors of safety
- The consequences of failure.

For these are still the main issues and difficulties—although we now are better able to communicate, calculate, and have (sadly) more case histories of the failure of tailings facilities.

2 UMTRA

2.1 Nelson et al...

The Uranium Mill Tailings Remedial Action (UMTRA) Project prompted the first appearance of formal papers on the application of risk assessment methods to tailings facilities. The focus of academics and consultants vying to get consulting contracts with the Department of Energy (DOE) was on the long-term stability of such facilities.

Nelson et al in 1983 prepared a NUREG document that appears to have used fault trees to examine the long-term stability of uranium mill tailings facilities. They included consideration of failure due to: erosion; gully formation; river shift; rip rap weathering; and differential settlement.

2.2 Van Zyl and Robertson

From 1987 we have a paper by Van Zyl and Robertson on probabilistic approaches to the long-term stability of uranium tailings impoundments. They discuss and give examples of Fault Trees in defining the probability of failure of uranium mill tailings facilities. Their focus is cover failure and control structure failure. They specifically exclude consideration of the consequences of failure, so strictly they do not consider risk per se.
They emphasize: “The selection of failure modes and their combination is a very important part of the probabilistic analysis.” This conclusion still echoes with us today, for how few tailings facility evaluations explicitly describe or analyze failure modes and their combinations. Once the dust settles on the Samarco failure, I suspect we will learn that many failure modes combined to create a vast failure.

2.3 What we Did.

In 1985 I joined the UMTRA Project as Manager of Engineering. By then the standard design adopted to deal with the issues of the probability (and risks) of long-term failure were already in place. On the basis that the law required stability of 1,000 years to the extent reasonably achievable and at any rate for 200 years, we did the following:

- Relocate tailings from unsuitable sites to geomorphically stable sites (14 of the 24)
- Shape the pile sideslopes to five horizontal to one vertical
- Place a thick layer of clay as a radon and infiltration barrier
- Place fine sand to act as a filter and erosion control layer between the clay and the overlying erosion resistant layer
- Place durable rip rap rock as the upper erosion control layer.

The ongoing stability of these piles attests to the following:

- In the presence of clear legislation, risk assessments may not be applicable
- Conservative, stable (low risk) closed tailings facilities are feasible, albeit expensive.

3 OSKAR STEFFEN.

In 1987, Oskar Steffen wrote what is probably the first paper on the use of risk assessment applied to non-uranium tailings facilities. He notes:

“The stability of tailings dams is dependent on many factors. These factors range from management techniques, the natural hazards and the engineering properties of materials. A statement on the safety of such a structure must incorporate the risks associated with all elements contributing to the stability of the structure. The author suggests that well established probability techniques are adequate in providing a reliable measure for dam safety. It is also recommended that the engineering judgment which has formed the basis for acceptable factors of safety in the past can be incorporated into defining acceptable probability criteria.”

Oskar Steffen does not make a clear distinction between the probability of failure, \( p(F) \), and the risk of an event, now formally defined as the product of probability and consequence,

\[
\text{Risk} = p(F) \times c(F).
\]

He notes the idea of reliability, which may be defined as \( R = 1 - p(F) \). He does not note the current concept of a Reliability Index, \( \beta \), which may be defined by this equation:

\[
\text{Reliability Index} = \beta = \frac{\mu_{FS} - 1}{\sigma_{FS}}
\]

where \( \mu_{FS} \) is the mean factor of safety and \( \sigma_{FS} \) is the standard deviation of the factor of safety. If the factor of safety is normally distributed, then the Reliability Index is uniquely related to the Probability of Failure by this equation

\[
p(F) = 1 - \Phi(\beta) \quad \text{where} \quad \Phi \text{ denotes the area of the distribution curve less than unity.}
\]

In practice, Oskar Steffen had been working on the probability of failure of open pit rock slopes for many years before he wrote his paper. In the case of a slope failure in an open pit, the key issue is the probability of failure as a function of the slope inclination. Thus he continued:
“The major contributory areas to risk in the case of a tailings impoundment may be grouped under the following classes:

(i) Unknown parameters, e.g., undetected geological features within the foundations, i.e., faults, weathered zone, dykes, etc.

(ii) Incomplete definition of parameters, e.g., physical properties of foundation soils and tailings material.

(iii) Assumptions inherent in design methods, e.g., sizing of drains of stability calculations.

(iv) Operating techniques, e.g., size and location of pool, material distribution within the dam.

(v) Natural hazards, e.g., storm events, seismic events – natural or mining induced, etc.”

In retrospect, Oskar Steffen pinpointed the causes of failure of Mount Polley, including undetected geological features, incomplete definition of parameters, and operating techniques.

4 BC HYDRO

British Columbia Hydro in 1993 issued guidelines for the application of risk assessment to water dams. They stated:

- “Dams should not impose intolerable risks on any individual.
- The risk imposed on society by each dam should be sufficiently low as to be considered tolerable.
- The safety of a dam should be proportional to the consequences of its failure.
- Risks of financial losses beyond the owner’s ability to finance should be as low as to be considered negligible.”

Commenting on this in 1996, Vick wrote:

“The former reluctance to incorporate formalized risk analysis procedures in dam safety practice was noted earlier, and perhaps when dam safety funds were more forthcoming there may have been less compelling need to do so. However, a growing body of experience by BC Hydro and others shows that risk analysis methodologies, if tailored specifically to dam safety protocol, can not only address requirements for risk-based financial justification, but can also improve engineering insight in ways that supplement, not replace, conventional practices. Although much development remains, BC Hydro’s commitment to risk analysis reflects its belief that these techniques will continue to enhance its dam safety program.”

None of this entered into mining. BC Hydro does indeed have a safe dam record. Not so the Ministry of Energy and Mines that did not adopt a similar approach to tailings dams that it regulates.

5 THE GREAT AUTHORS

In practice very little activity or advance in the application of risk methods to dam or tailings dams occurred for the next few decades. This in spite of some insightful comments by the great geotechnical engineers working in dam design.

In 1996, Robert V. Whitman wrote: “Thoughtful probabilists always emphasize that probabilistic methods do not replace traditional tools. Rather probabilistic methods are tools that can effectively supplement traditional methods, providing better insights into the uncertainties, and providing an improved basis for interaction between engineers and decision-makers.”
In 2002, Ralph B. Peck wrote: “When I have had the opportunity to review dam stability, the uncertainty has always been in the selection of appropriate shear-strength parameters. Not their values or variability, but whether the tests properly reflect field values. In its present state, risk analysis provides powerful insights into the relative importance of various factors affecting the safety of dams.”

While these statements note the value of risk methods, they give no guidance about how to go about doing risk assessments. Peck emphasizes the issue of the shear strength parameters, mainly those of the foundations. He foresaw the issues that lead to Mount Polley.

In 2002 Steve Vick’s book appeared. In *Subjective Probability and Engineering Judgment* he set out to explain and explore subjective probability, risk assessment, decision making, and the exercise of engineering judgment. His ideas did not enter conventional practice, probably because it is heavy reading. Even I could not bring myself to read it then. I have done so recently with more patience, and now conclude it should be mandatory reading for all tailings engineers who seek to avoid tailings failures.

6 ICOLD

One way to evaluate the advances in the application of risk assessment to tailings facilities, is to read the International Committee on Large Dams 2001 *Tailings Dams, Risk of Dangerous Occurrences—Lessons learnt from practical experiences.*

They note, almost in awe, the following fundamental but not informative or exhaustive insight:

“The risk assessment process will identify a number of risks associated with the tailings facility. The objective of the Risk Management Plan is to apply compensating factors to reduce the level of risk. The main areas of compensating factors include the following:

- Design [Approach & Details]: [The design approach and the details] may include civil works that increase the safety of the facility (e.g., berms), or additional technical and environmental studies that increase the level of confidence in the assessment.
- Security: This could include both passive and active security systems to safeguard the public and operating facilities.
- Monitoring and inspection programs: This allows early response to changes and identifies conditions which may be changing over the life of the facility. This includes the requirements of quality assurance and quality control throughout the operations.
- Maintenance programs: These include such items as maintenance of diversion and water management structures, collection or treatment facilities, access roads, etc.
- Management: This includes supervision requirements, training of staff, reporting and Corporate/Public assurance.”

7 MINING ASSOCIATION OF CANADA

In the 2011 *Guide to Audit and Assessment of Tailings Facility Management*, the Mining Association of Canada discusses the use of risk assessments in these words:

“Review the risk management system. Evaluate how it addresses:

- Hazard identification, risk assessment and risk management, including definition of unacceptable risk;
- Appropriateness of the hazard identification methodology for the facility and its unique issues (e.g., what-if, what-if checklist, potential problems analyses, failure modes effects analysis, hazard and operability studies);
Training for personnel involved in risk management (e.g., issues identification, risk assessment, ranking);
Ranking and prioritizing risks, setting action thresholds (risk tolerance) and communicating the results of risk assessments;
Maintaining a risk register to ensure that issues raised are not eliminated until actions are taken, or the risk reassessed and found to be below an acceptable threshold;
Recommendations for mitigation of unacceptable risks; and
Ensuring that risk assessments are current and adequately reflect current conditions, operations and processes."

In spite of promises, most mines did not do this. The British Columbia Ministry of Energy and Mines found that failure by Imperial Metals to do this was a root cause of the Mount Polley failures, and I suspect we will find that this is also a root cause of the Samarco failure—soon after the failure of Samarco, BHP announced that they used Failure Mode and Effect Analyses (FMEA) plots to manage the facility. That announcement was quickly wiped from the internet and I can no longer find it. Clearly FMEAs alone are insufficient.

8 FACTOR OF SAFETY

Traditionally tailings engineers have used the factor of safety as an overall, catch-all substitute for risk assessment or establishing the probability of failure. As the following brief discussion shows, there was an unfortunate drift from high factors of safety to low factors of safety in tailings practice, partially a result of overconfidence and partially as a way to save money.

In 1965 Cassagrande wrote:

“An embankment is to be built on a clay foundation. From his investigations the designer concludes that the in situ shear strength of the clay may range between 1 and 2 tons per sq. ft. If this project is an important dam whose failure would cause catastrophic losses, he might decide to use the very conservative design value of 0.6 tons per sq. ft. Thus, he would protect himself against the wide range of uncertainty by an ample margin of safety. i.e. with a factor of safety ranging between the limits of about 1.6 and 3.3.”

Meyerhof in 1983 wrote:

“The margin of safety in earthworks and foundation engineering depends mainly on the uncertainties and variability of the soil conditions and to a smaller extent on the variability of the loads, other than environmental loads, the approximations in the stability analysis, and the quality of construction. Customary total safety factors used in stability analyses relating to shearing failure and seepage considerations are, therefore, mainly governed by the degree of variability and uncertainty assessment of the soil resistance and the seriousness of failure.”

In 1999 the Canadian Dam Association set things on an erroneous path. For water dams they set these factors of safety:

- 1.3 during construction before fluid impoundment
- 1.5 during operation.

Tailings engineers seized on them and made them standard practice. Except perhaps Steve Vick who in 2002 had this sad commentary on the factor of safety used in tailings engineering:

“There was once a day, now lost in the fog of time, when some engineers got together—nobody really knows who—and decided what the minimum factor of safety should be for
various structures and analysis methods. These minimum factors of safety are now embedded in codes and standards of practice. The factors of safety in codes account for uncertainty and failure consequence, albeit in an unstructured way.”

The Canadian Dam Association fell totally into the trap when in 2014 they repeated these factors of safety in the Updated Application of Dam Safety Guidelines to Mining Dams. By then the damage was complete. Many tailings engineers were using 1.3 during the active life of the tailings facility and claiming that 1.5 applied only at closure. The argument was that the tailings facility is in construction when it is being operated, i.e., tailings deposited. The fact that the tailings are generally fluid seems to have escaped the profession.

The factor of safety of Mount Polley at failure was 1.3 or less and the regulators had accepted this as adequate. Most Brazilian tailings facilities have designed to a factor of safety of 1.3. If we assume that a factor of safety of 1.3 is normally distributed, the probability of failure is 0.3 to 0.4, nearly forty percent. No wonder Mount Polley and Samarco failed! One wonders how many incipient 1.3 facilities are out there just waiting to fail.

9 THE RECENT PAST

In 2014, Genki Taguchi completed a master’s thesis at the University of British Columbia of the use of fault trees in the analysis of tailings facility failure. In particular, he analyzed the failure of the Bafokeng tailings dam in 1974 using fault trees. This thesis is very valuable as a source of many possible fault trees that may govern tailings facility failure, and a clear exposition of how to compile and work with fault trees to gain insight into the causes and modes of failure. His fault trees emphasize this: there are most often many causes of failure that working together bring down the facility. There is seldom a single cause as is implied by so many lists of tailings failures and their “single” cause. We need more such studies.

In October 2015 my on-line course Risk Assessment, Decision-Making, and Engineering Management for Mine GeoWaste Facilities., was load on EduMine. It has proven poplar—although the topic has expanded faster than we can update the course.

10 THE PATH FORWARD

Many structural codes and many geotechnical codes dealing with foundations, retaining walls, and slope stability, have moved away from the use of a simple, one-size-fits-all factor of safety. The most recent is the 2014 Canadian Highway Bridge Design Code. Their new equation is this:

$$\phi_g R > \Sigma I_i \eta_i \alpha_i F_i$$

Where $\phi_g$ is a geotechnical resistance factor, $R$ is the characteristic geotechnical resistance (based on characteristic ground parameters), $I_i$ is a structural importance factor, $\eta_i$ is a load combination factor, $\alpha_i$ is the load factor, and $F_i$ is the characteristic load effect. It would take us far from our topic to discuss these factors. But it is clear this equation incorporates consideration of varying soil resistance, the importance of the structure (hence consequence of failure), varying load resistance ability (a probability function), and so on.

I submit the challenge to the tailings community is to come up with something similar. Of course it will take research and much discussion and deliberation to settle on the values for the various parameters as a function of site-specific factors. But I suggest this is a good and proper way to move forward to the goal of zero tailings facility failures.

11 CONCLUSIONS
The application and use of risk assessment in tailings facility management has stumbled and stuttered along in the past fifty years. Partly this reflects the inherent complexity of tailings facilities, the slow development of usable risk tools, and skepticism on the part of leading writers. Yet as Oskar Steffen said in 1987 with regard to the use of risk methods for tailings facilities:

- Well established probability techniques are adequate in providing a reliable measure for dam safety.
- Engineering judgment which has formed the basis for acceptable factors of safety in the past can be incorporated into defining acceptable probability criteria.”

With the great impact and great news dissemination of recent tailings failures, it is now more important than ever to heed his advice from so long ago.

REFERENCES


Meyerhof (1983) Safety factors and limit states analysis in geotechnical engineering. Canadian Geotechnical Journal. See also this link: https://www.youtube.com/watch?v=ksg4t_VlWxc


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