

Geotechnical Risk, Regulation, and Public Policy

N.R. Morgenstern

Abstract. At this time, there is a crisis associated with concern over the safety of tailings dams and lack of trust in their design and performance. This crisis has resulted from recent high-profile failures of dams at locations with strong technical experience, conscientious operators, and established regulatory procedures. It is the primary intent of this Lecture to assess the underlying cause(s) for this crisis, review the response to it by various agencies, and to make recommendations on how to overcome it. The Lecture begins with a review of the evolving safety culture associated with slope stability problems as exemplified by the achievements in Hong Kong. This is particularly relevant here because Victor de Mello was a key contributor to the recommendations made in 1976 that initiated the development of the Hong Kong Slope Safety System. The Lecture then addresses the evolution of the safety culture associated with water dams. While there is a long history of concern with respect to water dam safety, these concerns were intensified by several catastrophic dam failures that occurred in the USA in the 1970s. The evolution of regulatory systems from that time is recorded, as is the later trend to adopt risk-based safety assessment and regulation. However, the process that has emerged has been much affected by the Oroville Dam Spillway incident, and dam safety practice is being re-assessed by many. This Lecture summarizes some of the major findings arising from the analysis of this incident and makes recommendations to move to more performance-based risk-informed design and safety reviews that are constrained by reliable evidence to a greater degree than is currently the case. Turning to the evolving safety culture for tailings dams, this emerged with rational dam design procedures in the 1970s, more or less as an appendage to water dam design. The growth of environmental legislation related to surface water quality had a considerable impact as well. Hence, a twin regulatory regime emerged in the 1970s. The regulatory regime for tailings dams is typically more regional than national. The failure rate for tailings dams has generally been proportionately higher than water dams and thus has received considerable attention in the technical literature, however without measurable results. The recent failures of major dams in technically advanced regions of the world, operated by mature mining organizations and designed by recognized consulting engineers, has created a crisis in terms of a loss of confidence and trust associated with the design, construction, operation, and closure of tailings storage facilities. Responses to these failures are analyzed, and all are found wanting, particularly since the widespread evidence for weak engineering is inadequately recognized. The Lecture proposes a system for Performance-Based Risk-Informed Safe Design, Construction, Operation, and Closure of tailings storage facilities. It further urges the International Council on Mining and Metals (ICMM) to support the proposed system and facilitate its adoption in practice.

Keywords: safety culture, slopes, water dams, tailings dams, risk analysis, performance-based design.

In Memoriam

Like my predecessors who have delivered this Lecture, I too was much influenced by my relationship with Victor de Mello. Victor was inspiring in his breadth of interests, his enthusiasm, and his accomplishments. Reading the list of his consulting assignments is almost like reading the history of modern Brazil. This relates not only to his prowess as a consulting engineer, but also to his dedication to our profession as both a teacher and a researcher.

Over the years we engaged in numerous discussions on both technical and professional matters. I owe much to his guidance and support that encouraged me to become President of our International Society (ISSMGE). While we discussed a number of technical challenges over the years, the one in which we collaborated closely was the assignment from the Government of Hong Kong to partici-

pate in an Independent Review Panel on Fill Slopes, in 1976. The photo below (Fig. 1) shows Victor in characteristic field-work mode. As will be discussed subsequently in this paper, our report had a significant impact on slope safety in Hong Kong and subsequently on international practice.

Through engineering, Victor devoted his life to the betterment of the people not only of Brazil, but also the world at large. The central theme of this Lecture is public safety. I like to think that Victor would have approved of it.

1. Safe Slopes

1.1. Hong Kong slope safety management

The history of slope instability in Hong Kong is well-documented. In the 1970s, during a period of intensive construction, catastrophic landslides occurred in 1972 and

Norbert R. Morgenstern, Distinguished University Professor (Emeritus), University of Alberta, Edmonton, Alberta, Canada. e-mail: norbert.morgenstern@ualberta.ca.
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Figure 1 - Victor de Mello, 1976.

1976. They are portrayed vividly in videos and animation reconstructions online (GEO, 2011). Following the 1976 disaster, the Government of Hong Kong appointed an Independent Review Panel on Fill Slopes to advise on the cause and implications of the Sau Mau Ping failure. In addition to responding to the technical issues, the Panel also recommended “that a central organization be established within the Government to provide continuity throughout the whole process of investigation, design, construction, monitoring, and maintenance of slopes in Hong Kong” (Knill *et al.*, 1976, republished in 1999). The Government accepted this recommendation and established the Geotechnical Control Office (GCO), which later became the Geotechnical Engineering Office (GEO).

The GEO was set up in 1977 to regulate slope engineering in Hong Kong. The initial efforts of the GEO were based on the application of the then current state of practice in slope engineering in order to enhance the safety of man-made slopes in Hong Kong, at a territory-wide level. Over the ensuing years this involved cataloguing slopes and development of suitable prescriptive design measures and soil testing procedures, supported by considerable checking of designs proposed for construction, all of which contributed to the evolution of a safety culture of excellence. Advances were made in characterizing regional soils and geology, as well as carrying out slope stabilization works that were needed to bring priority slopes up to the newly declared standards. Within a decade, enormous progress had been made as reflected in a marked decline in the annual landslide fatality rate. It was recognized early that to reduce risk, a Slope Safety System had to evolve that not only set standards for new slopes, but also embraced retrofitting substandard slopes, issued landslide warnings, advanced emergency disaster services, and encourage public education on slope safety. This has been described in detail by Malone (1997).

Although considerable progress in reducing the risk from landslides had been made by the mid-1990s, Hong Kong continued to grow and public expectations of slope safety increased as the quality of life continued to improve. Unfortunately, several landslides occurred in the early to mid-1990s that generated a strong negative reaction from the community and the government administration. I returned to Hong Kong at that time to review the investigation into the Kwun Lung Lau landslide and to comment on the slope safety system as a whole (Morgenstern, 1994). This report resulted in a number of changes to GEO’s practice, leading to more outward-looking perspectives in evaluating slope stability assessments. Of far-reaching implications, it also supported the adoption in Hong Kong of the development and application of Quantitative Risk Assessment (QRA) as a tool for landslide risk quantification, evaluation, and mitigation. This was particularly timely as the GEO was beginning to address landslide hazards from natural slopes where traditional approaches based on prescribed Factors of Safety are of limited value. Malone (2005) recounts the circumstances that preceded this important step and the challenges associated with gaining acceptance for it within public policy. The outcome for the GEO and Hong Kong has been entirely positive.

Figure 2 plots the history of landslide fatalities in Hong Kong from 1948 to 2016. This history embraces a period of population rise, from about 2,000,000 to over 7,000,000 today. The threat of extreme storms and cyclones is ever present. Yet the impact of the GEO and its efforts on the key fatality metric is clear. This remarkable achievement is highlighted by the plot of the 15-year rolling average annual fatality rate, recently updated by Wong (2017), that emphasizes the near elimination of fatalities due to landslides in Hong Kong.

1.2. Learning from Hong Kong

The Hong Kong Slope Safety System increased its effectiveness as it progressed through traditional geotechnical considerations to risk-based decision-making, together with a parallel commitment to risk communication and enhancing public awareness. Are there lessons to be learnt from this experience that can be applied to enhancing safety of water and tailings dams?

Hong Kong was the first jurisdiction that put into regulation quantified tolerable risk criteria embracing geotechnical hazards associated with slope stability. While the methodology for QRA was well-established, and in some instances was a recommended practice, making it a required evaluation process in the law is much more complex than adopting it to aid decision-making in the private sector. Figure 3 presents the risk tolerance criteria adopted after considerable evaluation, and many examples exist in the literature to illustrate the calculations for risk associated with various scenarios.

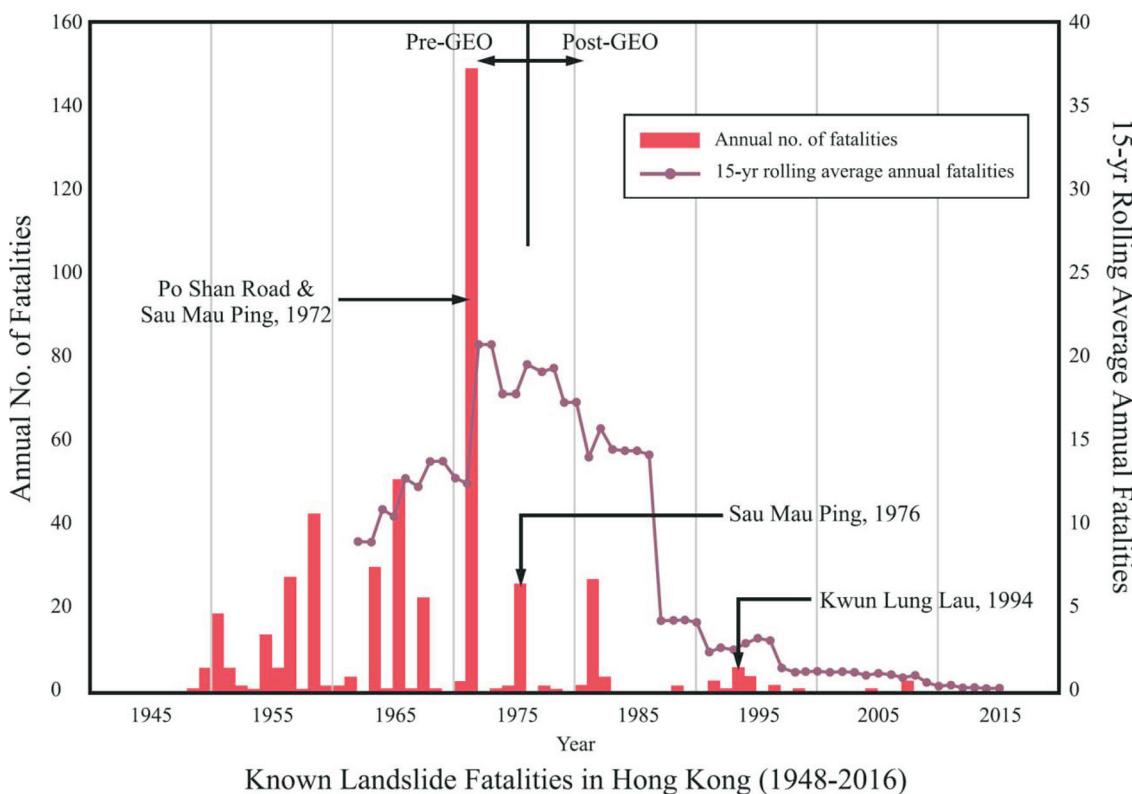


Figure 2 - History of landslide fatalities in Hong Kong from 1948 to 2016 (Wong, 2017).

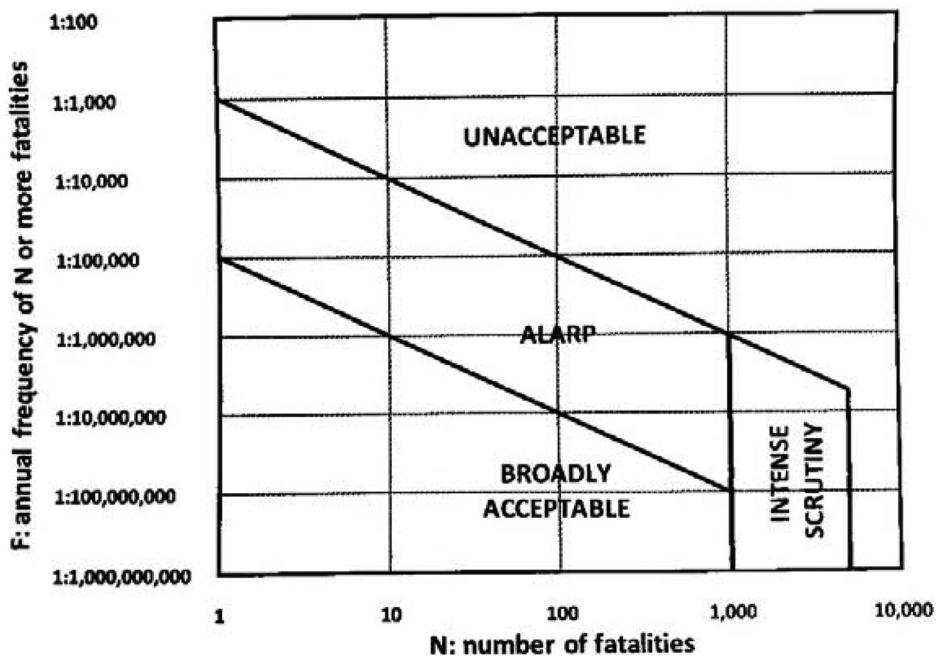


Figure 3 - Societal risk tolerance criteria for landslides in Hong Kong (GEO, 1998).

Hungr *et al.* (2016) undertook a review of current practice in various parts of the world related to landslide risk management and found wide differences between the current scientific understanding of risk acceptance and ac-

tual applications in practical circumstances. This is particularly marked by the absence of public jurisdictions to follow Hong Kong's lead. Examples of legally binding regulation in public policy were found only in Canada.

Two cases in Canada involving QRA are summarized in Morgenstern (2017). Both adopt the Hong Kong risk tolerability criteria (Fig. 3) and both relate to debris flows. In order to calculate risk in terms of “Potential Loss of Life” (PLL) in both cases, it was necessary to develop the hazard magnitude/frequency relationship based on complex geological and geomorphological studies; conduct debris flow runout analyses using advanced computational models; determine the spatial vulnerability reflecting both spatial and temporal probabilities; and convert the outcome into PLL metrics. QRA calculations are challenging undertakings but carry considerable weight if conducted carefully. While we found in both cases that the utilization of the Hong Kong criteria made sense, ultimately the stakeholders, jurisdictions and decision-makers have to select, ideally by means of a suitable public process, the appropriate risk evaluation parameters for a particular situation or jurisdiction. This selection of risk tolerance has to balance the risks from landslides with other societal values. Societal values include such things as public safety, affordable residential land, and return on investment. The geotechnical risk assessment can only inform this process.

While quantifying risk is challenging, communicating risk to inform public policy is equally challenging. In the case of the debris flow in North Vancouver, Canada, which was the first jurisdiction outside of Hong Kong to formally adopt the Hong Kong QRA criteria, extensive public involvement was a part of the process which ultimately resulted in legislation that places restrictions on increases of habitable area, rezoning, or redevelopment where tolerable risk criteria are violated. Tappenden (2014) has summarized these processes that successfully utilized a community task force approach. The District of North Vancouver received international recognition for its innovation and community engagement.

Similar circumstances were encountered in Canmore, Canada, the second jurisdiction in Canada to formally adopt QRA in legislation. This followed a catastrophic debris flow that created considerable damage, although, fortunately, no loss of life. Future risk mitigation was based on QRA. Risk communication had to be directed not only to the population affected, but also to three levels of government who would fund risk mitigation measures. The decisions affecting public policy required consideration of “feasibility, fairness, and affordability.”

The limited adoption of QRA in public policy related to managing landslide risk is better understood by reference to a Maturity Matrix for Assessing Community Engagement. This was published in studies undertaken to foster community resilience after the Katrina disaster in New Orleans (National Research Council, 2012). The matrix is presented in Fig. 4. As indicated by the Table, adoption of QRA into public policy requires a high level of Maturity (IV-V). Most jurisdictions worldwide operate in the range of I-III. Even with high levels of Maturity, the penetration

of QRA related to slope stability and related land management is slow.

In recognition of the fact that by far the greatest impact of landslide hazards occurs in the developing world, Hungr *et al.* (2016) were prompted to reflect that our approach towards landslide hazard and risk control should be made simpler and more transparent, so that it can be more easily exported to help people who most need it.

2. Safe Water Dams

2.1. History

A history of dams in society and their implications for public safety has been presented by Jansen (1980). Jansen observes that about 200 notable reservoir failures occurred in the world in the 20th century to the date of publication, with more than 8,000 fatalities. Catastrophic loss of life is always of great public concern, and, albeit in a reactive manner, this has resulted in a wide recognition of the need for governmental involvement in the supervision of dams and reservoirs.

Jansen (*op. cit.*) records how, in 1929, following the failure of the St. Francis Dam, California placed dams under an effective system of governmental supervision with jurisdiction over all dams, except those owned by the federal government.

In the United Kingdom, reservoir safety legislation came into effect in 1930 (The Reservoirs (Safety Provisions) Act, 1930) following two major dam failures in 1925 which led to the deaths of 21 people. This was subsequently updated with the Reservoirs Act of 1975. The Malpasset (1959) and the Vajont (1963) disasters also contributed to the trend in a number of countries to enact new or revised laws for the supervision of dams and reservoirs. However, it was the failure in the United States (US) of the Buffalo Creek Dam, in West Virginia, with 125 deaths and the failure of the Teton Dam in 1976, with 11 deaths and \$1 Billion in losses, which accelerated this process, not only in the US, but also elsewhere.

The Buffalo Creek Dam which failed in 1972, was actually a coal slurry impoundment that burst four days after having been declared “satisfactory” by a federal mine inspector. The effects were catastrophic for the local community, not only due to fatalities and injuries, but also due to devastating property damage. One of the results of this event, together with the near failure of the Van Norman Dam due to the San Fernando Earthquake and the failure of the Canyon Lake Dam, South Dakota, was the passage of the National Dam Inspection Act in 1972 which would have authorized the US Army Corps of Engineers (USACE) to compile an inventory of all dams in the US and inspect them. For both financial reasons and other, this was never completed.

The Teton Dam, Idaho, designed and constructed by the Bureau of Reclamation, failed during first filling. Fail-

Elements	Level I	Level II	Level III	Level IV	Level V	Examples of Possible Outcomes
Dam or levee safety reviews	No activity	Standards-based only	Introduction of additional review criteria (e.g., failure mode analysis)	Application of quantitative risk assessment by using criteria developed by owner or regulator with input from community members and stakeholders	Application of quantitative risk assessment by using criteria that reflect the community's societal values	Community is fully apprised of current level of risk
Other programs related to conventional dam/levee safety activities	Each tool is defined at different levels to show progression from minimum activity (Level I) through best industry practice to full community member and stakeholder engagement and collaboration (Level V)					
Emergency action plans	No activity	EAPs developed internally by owner	EAPs developed with input from emergency management agency	EAPs developed with input from community members and stakeholders and emergency management agency and shared with selected community representatives	Community collaboration with owners or operators to develop integrated EAPs that reflect community values	Community collaboration results in EAPs that minimize consequences of defined emergencies by incorporating community values and the potential for community resilience
Specific tools related to emergency planning response, including development of community preparedness measures, warning and evacuation procedures, and recovery plans	Each tool is defined at different levels showing progression from minimum activity (Level I) through best industry practice to community member and full stakeholder engagement and collaboration (Level V)					
Floodplain management	No floodplain management plans	Floodplain management plans in place	Floodplain management plans accommodate shadow floodplain associated with catastrophic dam or levee failure	Floodplain management plans integrated into community comprehensive or general plans	Floodplain management plans fully integrated into dam and levee owners' planning processes	Full participation by both community and dam and levee owners in floodplain management facilitates adoption of complementary resilience-enhancing measures
Specific tools such as those related to land-use planning and floodplain management, including initiatives for financial incentives and zoning reform	Each tool is defined at different levels showing progression from minimum activity (Level I) through best industry practice to community member and full stakeholder engagement and collaboration (Level V)					

Figure 4 - Maturity Matrix for Assessing Community Engagement (National Research Council, 2012).

ure was rapid. Fortunately, it occurred during the day. The population affected by the flood was estimated to be around 10,000, and, had the failure occurred at night, it is believed that the majority of those people would have been killed. This failure, the responsibility of one of the premier dam design, construction, and operation organizations in the world, sent shockwaves through the dam engineering community.

One positive outcome from the failure was the creation by the Bureau of Reclamation of one of the most rigorous and comprehensive dam safety programs in the US.

2.2. Evolution of regulatory systems

Public policy related to dam safety is established by regulations. It is of interest to observe the contrasting frameworks that have evolved. Some of the variations arise from differences in the legal structures in various countries, *i.e.*, the common law system *vs.* the Napoleonic legal system. Scaletta *et al.* (2012) provide some concise summaries.

In the US there are both federal and state dam safety regulations. Federal guidelines for privately owned hydropower dams are summarized in the Engineering Guidelines for Hydropower Projects (FERC, 2010). The guidelines were developed in conjunction with the Federal

Power Act. Dams that are owned and operated by the federal government through the USACE and the Bureau of Reclamation are regulated by their respective organizations. State or privately owned dams that do not support hydropower production, including tailings dams, are the jurisdiction of the individual state where the dam is located. All states in the US, with the exception of Alabama, have dam safety regulations.

US regulations typically have a hazard classification based on the consequences of failure. This classification commonly relates the loading conditions and the required Factors of Safety for design as well as requirements for monitoring and inspection. For high-hazard, FERC-regulated dams, the engineering guidelines also require the following:

- i. Supporting Technical Information Document
- ii. Emergency Action Plan
- iii. Probable Failure Mode Analysis
- iv. Dam Safety and Surveillance Monitoring Plan
- v. Dam Safety and Surveillance Report
- vi. Dam Safety Inspection Reports.

Similar requirements are required for high hazard dams from other federal and state agencies. The tenor of this phase of regulatory development is decidedly prescriptive and standards based. In more recent years, risk-infor-

med decision making has entered into federal dam safety evaluation processes, and this will be discussed below.

In Canada, the regulation of dams is on a provincial/territorial basis. The federal government has no mandate to regulate in this area. However, national dam safety guidelines have been published by the Canadian Dam Association (CDA), a professional organization which has no regulatory authority. A province may choose to adopt CDA guidelines which would then make them official standards in the specific jurisdiction. Matters are made more complex because regulations may differ in some provinces between water storage dams and tailings dams. CDA (2012) summarizes Canadian dam safety regulations by jurisdiction. Technical Bulletins published by the CDA provide additional detail on suggested methodologies and procedures for dam analyses and assessments.

While Brazil contains a large number of dams of considerable economic importance in terms of water supply, power generation, and support for industry and mining, prior to 2010 Brazil did not have any laws or regulations that addressed dam safety at either the federal or state levels. However, guidelines such as CDA and US federal agencies were available as a general reference for dam owners and hydropower plant operators. The lack of policy was remedied at the federal level in 2010 by the establishment of the National Policy on Safety of Dams and creation of the National System on Safety of Dams in Brazil (Presidente da República, 2010). The objectives of this law are to ensure compliance with dam safety standards, regulate dam safety requirements during various phases of the dam project, promote monitoring and oversight, institute public involvement, establish technical guidance, and foster dam safety culture and risk management. Comprehensive dam safety plans are required for dams assessed to be in higher risk categories.

The evolution of the regulatory system in Australia is of special interest. Like Canada, dam safety in Australia is covered by state legislation, and there is no role for the Australian federal government. Design methods were traditional until 1994 when the Australian National Committee on Large Dams (ANCOLD) produced Guidelines on Risk Assessment, followed by revised Guidelines in 2003. The Dams Safety Act was passed in New South Wales (NSW) in 1978, and it established the Dam Safety Committee (DSC) as regulator. By 2002, the DSC had officially decided to pursue a risk-based approach to dam safety regulation. This was endorsed by the NSW Government in 2006, and in 2010 it was fully implemented by the DSC. It is noteworthy that the DSC appears to have been the first regulator in the world to successfully incorporate the inclusion of public safety tolerability criteria into regulatory practice (Graham, 2016).

2.3. Evolution of risk-based regulation

The first phase of regulatory control of dam safety relied primarily on a prescribed standards approach supported by visual observations of behaviour amplified by instrumentation. USACE criteria dominated much of the practice. Spillway capacities were designed to safely pass an inflow design flood; Factors of Safety were calculated to meet required minimum values depending on various recognized loading conditions; and stress in components or the structure itself were compared with allowable levels and/or ultimate strengths. Dam failures were rare, and the methodology was underpinned by substantial experience. Brindled (2000) has provided an insightful analysis of the framework associated with risk-informed decision-making processes, summarized in Fig. 5. The description of the first phase of regulatory control fits well with Type A.

As summarized by France & Williams (2017), the evolution of risk analysis has strengthened the dam safety community in many ways by:

- i. Recognizing in a formal manner the many ways that a dam can fail and the consequences of the failures;
- ii. Using risk as a tool for prioritizing risk reduction actions, particularly for dam portfolio analyses; and
- iii. Focusing monitoring programs and remediation efforts on the highest risk dams and potential failure modes.

These are all laudable advances, although the means of achieving them are not without pitfalls.

As pointed out by France & Williams (*op. cit.*), dam safety risk analysis in the US has its roots in the Bureau of Reclamation's adoption of failure modes and effects analysis (FMEA) in the 1980s, which evolved into PFMA (potential failure modes analysis). This transformed the dam safety evaluation process into one of critically assessing the way dams could fail, along with the relative likelihoods of the different failure modes and their consequences. Steps in the process vary from qualitative to semi-quantitative. Detailed descriptions are found in Hartford & Baecher (2004) and FERC (2017). This methodology is utilized in practice both at the design stage and at subsequent performance evaluation stages. The requirement of FERC to conduct PFMA as part of its mandatory inspection for hydropower dams within its regulatory jurisdiction has resulted in widespread understanding and adoption of the procedures.

PFMA follows thought processes familiar to engineers; it can be applied to a variety of consequences (fatalities, property damage, environmental, etc.) with ease, and it can be conducted in a timely and economic manner under the right circumstances.

In the 1990s the Bureau of Reclamation advanced from PFMA to quantitative risk analysis as a key tool in dam safety decision making. This aided them in assessing the urgency of dam safety concerns and, particularly, the relative priority of concerns for different dams. Quantitative risk analysis consists of estimating annual probabilities

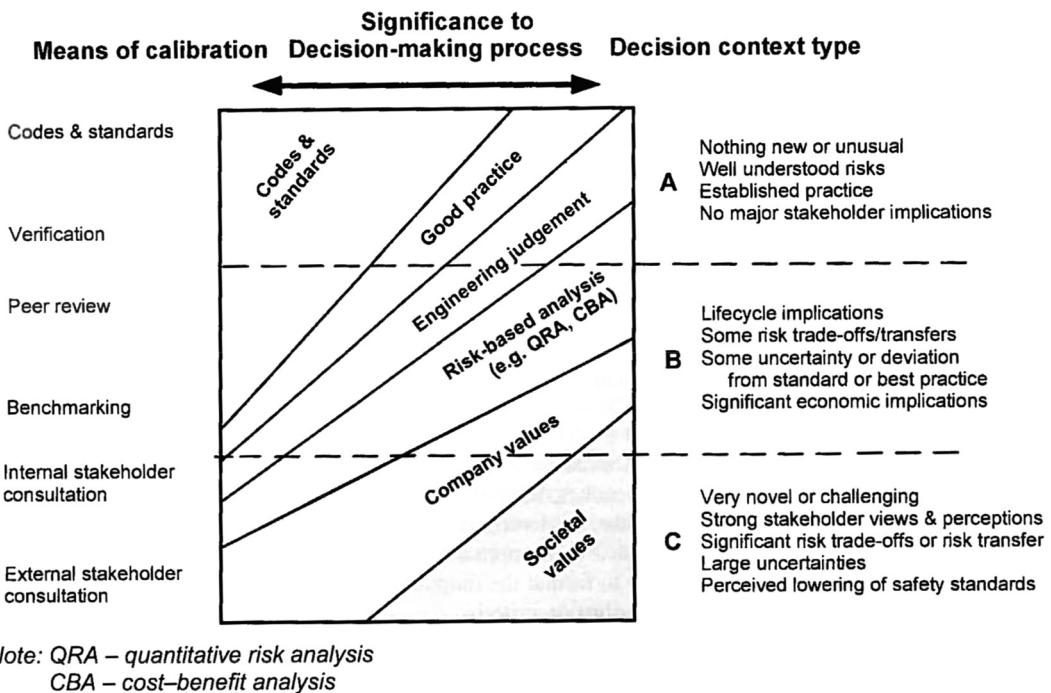


Figure 5 - Risk decision framework (Brindley, 2000).

of failure, failure consequences such as expected life loss, and annual life loss risks for failure modes of significance. Guidelines were needed to help evaluate the results of the analyses, typically expressed in terms of tolerable loss of life. This marks a significant change in metrics that might be acceptable internally to a large dam owner, but they should require extensive consultation if the criteria are to be adopted by the public at large. As observed by Bowles (2007):

“From the outset it is emphasized that judgements about the adequacy of dam safety, which are fundamentally judgements about public safety, are intrinsically value judgements and not technical matters, although they should be informed by sound technical information.”

The vocabulary of “tolerable loss of life” is provocative and should require stakeholder engagement as well as special risk communication efforts before the criteria become legal regulations. The appropriate balance between “value judgements” and technical matters also requires reflection.

While quantitative risk-informed decision making is undoubtedly informative, it involves its own, sometimes large, uncertainties. It is also time-consuming and costly. Embracing these uncertainties in a regulatory framework is challenging. This observation is also a finding arising from the previous discussion on the contribution of quantified risk analysis and its application to slope safety.

2.4. Dam safety after the Oroville Dam spillway incident

“Although the practice of dam safety has certainly improved since the 1970s, the fact that this incident hap-

pened to the owner of the tallest dam in the United States, under regulation of a federal agency, with repeated evaluation by reputable outside consultants, in a state with a leading dam safety regulatory program, is a wake-up call for everyone involved in dam safety. Challenging current assumptions on what constitutes “best practice” in our industry is long overdue” (Independent Forensic Team Report, 2018).

After the Oroville Dam Spillway incident in February 2017, FERC required the California Department of Water Resources (DWR) to engage an Independent Forensic Team (IFT) to develop findings and opinions on the causes of the incident. Anyone who cares about dam safety and is interested in the theme of this Lecture owes an enormous debt of gratitude for the outstanding report that has been produced. It is neither practical nor necessary to summarize the report in any detail before drawing conclusions from it. However, a brief description of the event is necessary before doing so.

The following points are extracted from the summary of the IFT report of the Incident which led to the mandatory evacuation of at least 188,000 people on February 13, 2017:

- i. The inherent vulnerability of the service spillway design and as-constructed conditions reflect lack of proper modification of the design to fit the site conditions.
- ii. Almost immediately after construction, the concrete chute slab cracked above and along underdrain pipes, and high underdrain flows were observed. The slab cracking and underdrain flows, although originally thought of as unusual, were quickly deemed to be “normal” and as simply requiring on-going repairs.

- iii. The seriousness of the weak as-constructed conditions and lack of repair durability was not recognized during numerous inspections and review processes over the almost 50-year history of the project.
- iv. Over time, a number of factors contributed to progressive deterioration (see Report for details).
- v. Due to the unrecognized inherent vulnerability of the design and as-constructed conditions and the chute slab deterioration, the spillway chute slab failure, although inevitable, was unexpected.
- vi. Once the initial section of the chute slab was uplifted, the underlying poor-quality foundation materials were directly exposed to high-velocity flows and were quickly eroded.
- vii. Although the poor foundation conditions at both spillways were well documented in geology reports, those conditions were not properly addressed in the original design and construction, and all subsequent reviews mischaracterized the foundation as good quality rock. As a result, the significant erosion of the service spillway foundation was also not anticipated.
- viii. In limiting service spillway discharge to reduce the likelihood of powerhouse flooding, the additional dam safety risk associated with use of the emergency spillway was not appropriately considered. Once the emer-

gency spillway was allowed to overtop, this additional risk was soon realized, and the evacuation order became a necessary precaution.

Figure 6 presents a picture of the net result of the Incident.

The IFT report makes a number of observations and recommendations related to the operation of DWR related to dam safety evaluation and with respect to the process as a whole. Two are particularly germane to the contents of this Lecture:

- i. “Shortcomings of the current PFMA processes in dealing with complex systems must be recognized and addressed. Evolution of ‘best practice’ must continue by supplementing current practice with new approaches, as appropriate.”
- ii. Compliance with regulatory requirement is not sufficient to manage risk and meet dam owners’ legal and ethical responsibilities.”

Vick (2017) has made a timely and important contribution by emphasizing how “normalization of deviance” (Vaughan, 1996) has been a major contributing factor in a number of dam failures or near failures. The Oroville Incident is clearly another example to be added to the list. Improvements to dam safety evaluation processes must



Figure 6 - Oroville Dam Spillway incident (Independent Forensic Team, 2018).

recognize this organizational risk and measures must be imposed to eliminate it.

2.5. Toward safer water dams

In the previous presentation summarizing the evolution in practice of risk-based perspectives for evaluating dam safety, the common regulatory requirements were described as standards based, albeit supported by observation. This is not an accurate description of geotechnical practice in design and construction for all but the simplest structures. It is common risk management in geotechnical engineering to employ the observational method, which requires not only making observations, but also planning for intervention and mitigation of risk if needed. As discussed in Morgenstern (1995), the observational method implies risk analysis, but of a consequential kind. Its application enhances robustness, adaptability, and the capacity for intervention which are important considerations to enhance reliability.

Current practice does require conformance to certain standards, some prescribed and some recognized empirically as sound practice. As such, the design process based on the observational method is precautionary and would best be described as a “*precautionary risk-informed design process*.”

The geotechnical aspects of current dam design, at least for major projects, is rapidly being transformed by advances in instrumentation, real-time monitoring, and interpretation of data, all supported by increased capacity, in real-time, to model and interpret deformation and seepage regimes. As observed by Morgenstern (2017), this will lead to design procedures that overcome some of the conceptual limitations associated with the Factor of Safety concept and, by sequential history-matching of performance and implicit Bayesian updating, will result in a more reliable basis for projecting future performance. This can be described as a “*performance-based risk-informed design process*.”

Whether precautionary or performance-based, or even utilizing subjective judgements based on experience, it is essential that the risk assessment process be constrained by evidence and its evaluation to a higher degree than is currently the case. Based on the IFT report on the Oroville Dam Spillway Incident and experience from forensic investigations into two major tailings dam failures (Mount Polley Internal Panel, 2015; Fundão Tailings Dam Review Panel, 2016), the following are recommended:

- i. Design Basis Memorandum (DBM): The DBM contains the design criteria for all aspects of the facility and the methods of analysis. It should contain enough detail to support a forward projection of all observational performance data once the project is complete and in service. Such an analysis should be undertaken to provide a reference basis for in-service expectations.

- ii. Construction Record: Experience reveals that when problems occur, the record is everything. Construction recordings should be expanded to develop a comprehensive GIS-based retrievable system that will document all aspects of construction history chronologically, as well as any written or photographic documents associated with the specific components.
- iii. Quality Assurance (QA): The role of QA is to document whether the facility has been constructed as intended. This is much more than simply collecting as-built drawings and some corroboration of laboratory procedures. More extensive reporting is needed tied to the expanded Construction Record.
- iv. Deviations: Deviation from the design/specifications are common. Major deviation may result in a formal design change which would be captured in the QA report and changes to the DBM. However minor deviations may accumulate. To avoid the risks associated with normalization of deviation, a Deviation Accountability Report (DAR) should be implemented to validate the acceptance of the deviations.

Implementing the above and carrying the related documentary references and criteria through the future dam safety evaluation process should contribute to improve reliability, accountability, and transparency, and thereby strengthen the safety cultures associated with the long-term performance of water dams.

3. Safe Tailings Dams

3.1. Regulatory framework

The industrial antecedents for the development of tailings dams differ markedly from those for water dams. Water dams, for millennia, created value by facilitating flood control, enhancing water supply, and subsequently expanding power supply. The disposal of tailings was a necessary evil in the mining industry, to be carried out at minimal cost. This typically meant disposal in streams or other bodies that would minimize accumulation. As production capacity increased in the mining industry, or aqueous disposal was not economical, surface stacking evolved. All aspects of tailings disposal added to the cost of production, and it was natural, at the time, to adopt procedures that were as economical as possible. This resulted in the upstream method of construction which became the standard procedure for many decades. By the mid-1960s changes were becoming evident.

The transformation is evident in the paper by Casagrande & McIver (1971). It provides a clear recognition of the differences between tailings and water dams as well as special geotechnical risks associated with upstream construction. The references reveal considerable related geotechnical studies being undertaken in the years preceding publication.

Klohn (1972) summarizes the evolution of tailings dams in British Columbia (BC, Canada), where methods of tailings dam design and construction were coming under critical review as both government regulatory bodies and the mining industry became more aware of the need for better tailings dams. This culminated in the Government of British Columbia enacting regulations which, historically, were precedent setting in North America. The BC regulations appeared in 1971, but were preceded by the Chilean decree in 1970 that banned upstream construction of tailings dams (Valenzuela, 2016).

In BC, two separate approvals were necessary: the first from the Department of Mines which was specifically concerned with the design, construction, and operation of tailings dam; and the second from the Department of Lands, Forests, and Water Resources, Pollution Control Branch which was concerned that the effluent escaping from a tailings storage pond would not cause pollution. The early guidelines related to dam safety were not prescriptive in any way, retaining confidence in the professional community to meet its obligations. At the time, practice procedures and other supporting documentation were being published to indicate what was considered acceptable practice.

The evolution of tailings dam regulation was much influenced by these two emerging regulatory concerns: i) environmental concern over pollution of water bodies, and ii) concern with respect to safety of dams. The history of the development of the Grizzly Gulch Tailings Dam, in South Dakota, is an example of the first, while Tar Island Dyke, the first tailings dam in the Alberta oil sands industry, is an example of the second.

In the US, the enactment of the Federal Water Pollution Control Act Amendment of 1972 brought an end to the standard practice of merely depositing tailings in the most convenient place. This legislation set a deadline of 1977 for compliance with standards that totally precluded disposal of industrial waste into the waters of the US. The Homestake Mine, which had at the time been operating for about 100 years, had been depositing most tailings into local creeks. To comply with these regulations, the Mine undertook the design and construction of an impoundment to water dam standards with an ultimate storage capacity of 50 years of gold production. Inflow flood design criteria were declared by the Mine Enforcement Safety Administration (MESA), but geotechnical design criteria relied on the experience of the dam design engineers. Site investigation was performed in the mid-1970s. The design was finalized in 1975, and the facilities were completed in 1977, with subsequent raises at later times. Details are provided in Carrigan & Shadrick (1977). I was involved with this facility at the end of its service life and was pleased to assess the safe design created at the outset.

A contrasting evolution of tailings dam regulation is provided by the experience in the Province of Alberta arising from the expansion of dam safety regulation, discussed

in Section 2, above. In 1978, the Government of Alberta enacted specific dam and canal safety regulation establishing the first formal dam safety regulatory program in Canada to ensure safety of the public and the environment. This followed from recommendations of a Committee formed by the then Association of Professional Engineers, Geologists and Geophysicists of Alberta in 1972, that recommended that the Province of Alberta take action in this regard. The initial application of this new regulatory program was to Tar Island Dyke, the first tailings dam under construction in what was a relatively young oil sands industry. This first comprehensive safety review conducted by a team of well-known experts in the field expressed concern about movements in the foundations of the structure that had been detected by inclinometers that had been installed, and recommendations were made to restrict rate of construction by observational means. As noted by McRoberts *et al.* (2017): "This first review significantly strengthened the ability of the geotechnical engineers to insert on the budgetary support for appropriate monitoring with such new-fangled devices such as slope inclinometers and pneumatic piezometers."

The positive interaction between the new regulatory process and the growing challenges in the oil sands industry contributed to the evolution of dam safety reviews, now regularly being undertaken, and the early adoption in the industry of external tailings review boards.

Both the catastrophic failure of the Aberfan Coal Waste Dump in England in the 1960s and the equally catastrophic failure of the Buffalo Creek Coal Waste Dam in the US in 1972 resulted in the recognition in the dam design community that tailings dams and related structures required better design to increase their safety. A committee to address these issues was formed by the International Commission on Large Dams (ICOLD) in 1976 which produced a design manual in 1982 (ICOLD, 1982). This publication (Bulletin No. 40) contained a summary of the status of international regulations that revealed that only limited progress had been made related to tailings dam safety by the time of completion of the manual.

ICOLD (1989) issued Bulletin No. 74 in response to the increasing number of large tailings dams that were being constructed around the world and in recognition of the severe consequences that would result from failure. The Stava catastrophe that occurred in Italy in 1985 was cited as an example. This publication, in an Appendix on Guidelines on Tailings Dam Legislation, recognized that while regulation of water dams had advanced, only a few countries had similar measures for tailings dams and that the jurisdictional issues for regulation of tailings dams were complex. They could vary from national to regional and even local responsibilities. Recommended guidelines were published but, to my knowledge, are not commonly cited.

Failures persisted in the following years and the environmental impact of tailings dams also attracted the atten-

tion of the United Nations Environmental Programme (UNEP) who joined forces with ICOLD to support a substantial revision of Bulletin No. 40 in the form of ICOLD/UNEP (1996). Progress was identified in recognizing jurisdictions that had regulations covering tailings dams, particularly with respect to environmental matters. Regional jurisdictions were the norm in North America and Australia where strong mining industries existed. However, national regulations also prevailed elsewhere at this time, such as in Chile.

3.2. The emerging crisis

Recorded failures of tailings dams persisted through the 1980s and 1990s with even an increase in rate in the mid-1990s as reflected in the WISE inventory (www.wise-uranium.org/mdaf.html). This attracted the attention of not only geotechnical and mining engineers, but also other organizations such as the UNEP.

In 1996, I presented an overview of the multiple contributions that geotechnical engineering can make to the challenges of mine waste management (Morgenstern, 1996). This presentation emphasized the changes in design and performance requirements that have evolved in recent years, and it provided examples of complex tailings dam behaviour, both favourable and not, as illustrations of the need to avoid over-simplification.

Toward the end of the decade, the UNEP combined resources with the International Council on Metals and the Environment (ICME; now the International Council on Mining and Metals, ICMM) to convene international meetings on managing the risks of tailings disposal. At the meeting in 1998, I drew on the previously published assessment, aided by additional experience, to conclude the following (Morgenstern, 1998):

- i. The standard of care associated with mine waste retention structure was too low.
- ii. The standard of care associated with mine waste retention structures should move towards those of water-retaining structures.
- iii. Establishing the standard of care is the responsibility of senior mine management who should set design objectives, risk management policy, and the associated levels of safety.
- iv. Consultants should involve Failure Modes/Effects Analysis or equivalent risk analyses at an early state of project development.
- v. Regulatory Agencies should devote more concern to the details of corporate policy regarding mine waste management procedure as opposed to being risk driven.
- vi. ICME (now ICMM), as the industrial interface, should contribute to improved risk management by drafting model corporate policy codes of practice and model regulations for consideration by individual corporations and regulatory agencies.

As will be borne out by this Lecture, it is disappointing to reflect that these recommendations are as meaningful to-day (2018) as they were when presented twenty years ago (1998).

I re-visited the issue of the safety of mine waste impoundments in 2010 (Morgenstern, 2010). In the preceding decade, failures continued to accumulate at approximately the same rate as in the recent past although some analysis suggested the possibility of a correlation between the time of failure with commodity price peaks. The inference implied here would be the suggestion that economic prizes create compromises in the diligent management of tailings. There was no socio-economic pattern among the cases, with regulatory environments ranging from weak to strong.

I was able to draw attention to some positive developments, namely:

- i. The efforts made by the Mining Association of Canada (MAC) to foster improvements in the safe and environmentally responsible management of Tailings and mine waste. This culminated in the document "MAC Guide to the Management of Tailings Facilities" which provided a framework of management principles, policies and objectives, checklists for implementing the framework through the life cycle of a tailings facility, and lists of technical considerations. This document was followed by the guide on "Developing an Operation, Maintenance, and Surveillance Manual for Tailings and Water Management Facilities" and "A Guide to Audit and Assessment of Tailings Facilities Management." The MAC guidelines were readily adaptable to non-Canadian jurisdictions and site conditions of any kind.
 - ii. Improvements in regulatory guidance documents had been produced, particularly with respect to the coal industry in the US where serious problems with the integrity of coal waste impoundments had developed early in the decade. Nevertheless, the limitations of relying on regulatory processes alone to ensure dam safety were becoming increasingly clear.
- At the time, I offered the opinion that in my experience the dam safety system that had been developed in Alberta applied to the oil sands industry was the best in the world. It is worth repeating its components:
- i. Each owner is cognizant of its responsibilities to provide a tailings management consistent with the MAC guidelines.
 - ii. Each owner has staff qualified in the management of tailings dams.
 - iii. Owners retain consulting engineers for design and construction supervision who are well-known for their expertise in tailings dam design with special reference to the circumstances associated with the oil sands industry; the designer acts as the Engineer-of-Record at least for design; senior internal review of design submissions is expected.

- iv. Designs rely on the detailed application of the observational method for risk management.
- v. Designs are reviewed by the Alberta Dam Safety Branch, the regulator, who have staff well-versed in dam design and construction.
- vi. An annual report is submitted to the regulator by the owner, supported by the Engineer-of-Record, that the dam is behaving as intended; if not, actions that have been or need to be taken are indicated.
- vii. In accordance with CDA Guidelines, approximately every five years the owner retains an engineer, other than the Engineer-of-Record, to undertake an independent assessment of dam safety.
- viii. Each owner retains an Independent Geotechnical Review Board, comprised of senior specialists, to provide on-going third-party review of geotechnical issues of significance to the operation. One of the major responsibilities of such Boards is to review all aspects related to safety of tailings dams over the life cycle from design, construction, operation, and closure.

The success of the dam safety system applied to the Alberta oil sands industry relies on responsibilities shared by the owner, the Engineer-of-Record, the regulator, and various levels of independent review. I am aware that in many jurisdictions, not all of these components will be mature. Under these circumstances, the remainder of the safety management team should exercise additional caution to compensate for regional limitations. As many case histories continue to remind us, a permit to operate is not a guarantee against failure.

It is of interest to note that this same regulator has not had the same degree of success with a different set of industrial clients, strengthening my view that improving the safety of mine waste impoundments relies on shared responsibilities and cannot be achieved by regulation alone.

In this same presentation, following my experience with the oil sands industry and with water dams, I advocated for increased use of Independent Tailings Dam Review Boards (ITRB) in the mining industry and provided some guidance on their operations. It is of interest to note that McRoberts *et al.* (*op. cit.*) confirm the value of ITRBs in their experience in the oil sands industry.

Following on from 2010, tailings impoundment failures continued to recur at approximately a constant rate, as reflected by the WISE catalogue, which is recognized to be incomplete. For example, Li *et al.* (2016) report four major failures of upstream dams in China over the period 1962–2010 that involved 249 fatalities and are not included in the WISE catalogue. Moreover, Li *et al.* (2017) reveal that following a period of eliminating particularly hazardous facilities, at the end of 2015, 8,869 tailings facilities existed in China. Most are upstream constructions with design Factors of Safety less than commonly used elsewhere. Details are not readily available.

However, outside of China, the record for 2010 to 2018 was not “business as usual.” In 2014, the Mount Polley Mine tailings dam in British Columbia failed, fortunately with no loss of life, but with substantial outflow of both water and tailings. This was followed by the failure of Samarco’s Fundão tailings dam in 2015, with multiple fatalities and huge environmental and social consequences. It is located in Minas Gerais, Brazil. These two events attracted special attention not only because of their scale of consequences, but perhaps more so, because of their provenance. Both were operated by responsible mining companies, retaining experienced consulting engineers, and both were located in regions with mature mining experience and advanced regulatory regimes. The conjunction of the two events, building on a long history of inadequate performance has created to-day’s crisis. There is a loss of confidence and a loss in trust in the safety of tailings dams. Moreover, there is a lack of transparency in the way that safety-related issues are communicated to stakeholders.

In its commentary on risk reduction in the Mount Polley Report (Independent Expert Panel, 2015), the Panel expressed the following:

“In risk-based dam safety practice for conventional water dams, some particular level of tolerable risk is often specified that, in turn, implies some tolerable failure rate. The Panel does not accept the concept of a tolerable failure rate for tailings dams. To do so, no matter how small, would institutionalize failure. First Nations will not accept this, the public will not permit it, government will not allow it, and the mining industry will not survive it.”

As this manuscript is being written, Newcrest Mining Limited (NML) has just announced the failure of a portion of its tailings dam at the Cadia Mine in New South Wales, Australia. NML is one of the largest and most experienced gold mining companies in the world; its Cadia Mine is its flagship producer; and New South Wales has had for some time one of the most comprehensive dam safety regulatory processes in the world. Clearly the crisis is not over.

3.3. Responding to the crisis

3.3.1. Introduction

As a result of the two main incidents a few years ago, many commentators and agencies addressed the issues and provided guidance to resolve the crisis. This involved individuals, mining organizations, NGOs, government, and the UNEP. This section summarizes and comments on the most noteworthy of these recommendations and actions and asks the overarching question whether enough has been done.

3.3.2. Prescriptive recommendations

Examples of prescriptive recommendations follow with commentary on their effectiveness.

3.3.2.1. “Ban upstream dams, particularly where subjected to seismic loads.”

This prescriptive solution has appeal because of the large number of upstream failures in the case history records, and it is policy in Chile where, since 1970, the construction of upstream dams has been prohibited. This results in higher costs. Nevertheless, the policy was reaffirmed in 2007 with no exceptions. Valenzuela (2015) summarizes the successful performance of downstream tailings dams in Chile when subjected to large earthquakes, hence, apparently, vindicating the policy.

However, I side with the views of Martin & McRoberts (1999) and others before them (*e.g.*, Lenhart, 1950; Vick, 1992) that there is nothing wrong with upstream tailings dams provided that key principles are adhered to in the design, construction, and operation of such dams. Some 12 principles are outlined that should be recognized when upstream dams are proposed. In my practice, I advocate for purposes of preliminary design that liquefiable deposits that can liquefy be assumed to do so and that containment be provided by a buttress of non-liquefiable unsaturated tailings and/or compacted dilatant material. In addition, it is essential to continually demonstrate by monitoring that the assumed unsaturated conditions in the buttress persist if relied upon in the design and that the buttress is behaving as intended.

Some upstream dams are surprisingly seismic resistant. Morgenstern (1996) cites studies into the Dashihe Dam that survived the catastrophic Tangshan earthquake in 1996. At the time of the earthquake, this dam was 36 m high and the downstream slope was 5:1. It developed some cracking and sand boils during the earthquake, but did not collapse. Investigation carried out by a joint Sino-Canadian research team revealed surprisingly high densities. These were attributed to the low solids content during deposition and long beach slopes facilitating enhanced seepage-induced densification. The capacity to pump higher solids content slurry did not exist in China at that time. While a rational explanation of behaviour exists, the survival of the Dashihe Dam was more accidental than founded in geotechnical principles.

If upstream construction can be executed safely, even in seismic areas, does that contradict the logic of the Chilean regulation? The Chilean regulation, as with most national/regional regulation, reflects more than design principles. It must reflect the maturity of the design community, procurement policies, quality assurance, land tenure, the degree of seismicity, and many other aspects of practice. Only the Chileans have the capacity to make these integrated judgments with respect to public safety in their own country.

3.3.2.2. “Ban clay foundations.”

There are numerous examples of successful construction of large tailings dams on clay foundations. From the oil

sands industry alone, one can cite the successful completion of Tar Island Dyke, 90 m high, in part on a normally consolidated alluvial clay and other structures, albeit with flat slopes, on some of the weakest foundation ever encountered.

The application of geotechnical principles adequately provides for accommodating clay foundations. The challenge resides in ensuring that these principles are properly understood and applied in design.

3.3.2.3. “Require a Factor of Safety of at least 1.5 during operations.”

The prescription of the Factor of Safety (F of S) is attractive to regulators, but experience with case histories, such as Samarco, reveal that over-reliance on prescribed values is not adequate to eliminate failure. In my experience, we have been using F of S = 1.3 during operations on very challenging sites in the oil sands industry for many years. At the other end of the spectrum, I have encountered cases where F of S = 1.5 may not be adequate due to either enhanced ductility or enhanced brittleness. The prescription of F of S in regulation, if necessary, requires thoughtful input from experienced designers and recognition of the characteristics of regional practice.

This leads to a wide choice in regulatory perspectives from that adopted in Chile where upstream construction is banned regardless of calculated F of S, to that currently being adopted in the revised Alberta Dam Safety Guidelines where no specification of minimum F of S is made. In this instance, existing industry guidelines are referenced, but the selection of the F of S must consider influencing factors such as:

- i. Consequence of failure
- ii. Uncertainty of material properties and subsurface conditions
- iii. Variable construction and operating conditions
- iv. Comprehensive site investigation, and geotechnical monitoring
- v. Soil response (contractive/dilative) and its variation with confining stress and shear stress laws), including potential for brittle failure
- vi. Time-dependent, deformation-dependent, and stress-path dependent processes that may affect the critical material properties
- vii. Strain incompatibility of different materials
- viii. Seismic loading as appropriate
- ix. Implementation of an effective risk management system (*e.g.*, observational method).

3.3.2.4. Concluding remark

No set of simple prescriptions will resolve the crisis. As emphasized by McRoberts *et al.* (2017): “One of the most important learnings can be seen in failure of other structures in the world. This is that a highly integrated team effort and success of an individual structure relies on the

operational discipline of planning, technology, operations, geotechnical engineering, and regulatory bodies.”

3.3.3. Response in British Columbia (BC) to the Mount Polley incident (2014)

The breach in the Mount Polley Tailings Storage Facility (TSF) resulted in two inquiries:

- i. Independent Expert Engineering Investigation and Review Panel (<https://www.mountpolleyreviewpanel.ca/final-report>).
- ii. Investigation Report of the Chief Inspector of Mines (<https://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/further-information/directives-alerts-incident-information/mount-polley-tailings-breach/mount-polley-investigation>).

The first had terms of reference to report on the cause of failure of the tailings storage facility and to make recommendations to government on actions that could be taken to ensure that a similar failure does not occur at other mine sites in BC. The Panel concluded that the dominant contributions to the failure resided in its design and operation. In addition, it recommended that the industry establish a path to zero failure, as opposed to some tolerable failure rate. To do so, it should adopt a combination of Best Available Technology (BAT) and Best Available Practices (BAP). BAT argued for an emphasis on technologies that minimize the consequence of failure by reducing fluidity and/or provide more positive containment. BAP included a number of recommendations to reduce the probability of failure by improved governance, expanded sensitivity to risk assessment in design, the introduction of Quantitative Performance Objectives in the declared design, the increased utilization of independent tailings review boards, and other related aspects of professional practice.

The Chief Inspector of Mines has the statutory authority to investigate any incident that occurs on mine sites in the Province of British Columbia. His investigation differed from that of the Independent Panel in that it included the determination of the root and contributory causes of the event as well as developing findings to address the accountability of the industry, the regulator, engineering practices, and any other contributions to the event. The investigation was also concerned with reducing the risk of such an event in the future, as well as making recommendations for regulatory changes.

The technical explanation of the failure was similar to that presented by the Independent Panel, but it went further in attributing the root cause to weak engineering, waste management issues, and risk management. It is of interest to note that the facility, from a structural perspective, was apparently not in contravention with the then-extant regulations, clearly prompting a need for a reassessment. Arising from the lessons learned from this inquiry, multiple recommendations for improved practice were made to mining op-

erations, the mining industry, professional organizations, and the regulator. There was a strong alignment between the recommendations arising from the two investigations.

The Government of British Columbia responded positively to the recommendations from the two inquiries. In particular all of the recommendations arising from the Independent Panel have been addressed, and a major revision of the Code has been completed and published (Health, Safety and Reclamation Code for Mines in British Columbia; revised June 2017 <https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/contracting-with-the-province/documents/12811-2018/t3-10-health-safety-and-reclamation-code-for-mines-in-british-columbia-2008.pdf>). Chapter 10 (Permitting, Reclamation and Closure) in the Code deals with tailings storage facilities. The revised Code reflects the response of a multi-stakeholder committee to the findings from the inquiries. This is an important document and, in my view, constitutes the best revision of any regulatory document in response to the crisis. It is evident that both BAT and BAP need formalized response and that regulation needs to be more prescriptive than in the past to minimize recurrence of the failures that are being encountered. This Code strikes a sensible balance in this regard without intruding into the responsibilities of both the operator and the design engineer.

It is of interest that it is having influence elsewhere. For example, the State of Montana has recently adopted a regulatory process that draws considerably from the example of the BC Code.

3.3.4. Response in Brazil to the Samarco incident (2015)

The Report on the failure of the Fundão Dam (Fundão Tailings Dam Review Panel, 2016) was limited to an evaluation of the technical causes of failure. It drew attention to flaws in both design and operation. However, it consciously did not address roles and responsibilities. Public discussion of these issues is limited by ongoing litigation. However, this has not prevented agencies in Brazil from assessing changes in both professional practice and regulation, intended to prevent future reoccurrences of such incidents.

The Brazilian National Dam Safety Policy was first established in 2010 and constitutes the regulatory framework for dams in the country. Oliveira & Kerbany (2016) provide a brief summary of the evolution of tailings dam risk in Brazil and their regulations up to the Samarco incident. ABNT NBR 13028:2006 appears to have been the first regulatory instrument explicit for tailings storage facilities. Following Samarco, a committee was formed to revise the existing regulations, and in November 2017, a new version 13028:2017 was produced. It expands considerably on the technical requirements to support approval of the design of a tailings dam and draws on relevant international practice in this regard. In addition, the National Department

of Mineral Production (DNPM) has expanded substantially its regulatory requirements with respect to the operation of tailings facilities (Alves, 2017) and additional requirements may be forthcoming.

The role of the State in Brazil from a regulatory aspect is not immediately clear. Bogossian (2018) reflects disappointment with the rate of change of regulations governing tailings dam safety.

3.3.5. Response of United Nations Environment Programme (UNEP)

The UNEP has demonstrated a long-term concern regarding the high incidence of inadequate performance of mine tailings storage facilities. In response to the emerging crisis, it undertook a Rapid Response Assessment to look at why existing engineering and technical knowhow to build and maintain safe tailings storage facilities is insufficient to meet the target of zero catastrophic incidents. It examined the ways in which the established best practice solutions to international collaborative governance, enhanced regulations, more resource-efficient approaches, and innovation could help to ensure the elimination of tailings dam failures. Case histories were utilized to highlight efforts in this regard (Roche *et al.*, 2017).

This report has not been prepared by technical specialists, and it has been obliged to adopt some of the published literature at face value. Nevertheless, it is generally balanced, well-produced with helpful photographs, referencing, and historical summations. It concludes with two recommendations and identifies a number of actions to improve regulation and practice. The two recommendations are:

- i. The approach to tailings storage facilities must place safety first, by making environmental and human safety a priority in management actions and on-the-ground operations. Regulators, industries, and communities should adopt a shared zero-failure objective in tailings storage facilities where “safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor” (citation from Mount Polley Expert Panel Report, p. 125).
- ii. Establish a UN Environment stakeholders report to facilitate international strengthening of tailings dam regulation.

A number of actions recommended in past publications are also summarized. Clearly the first recommendation is consistent with the emerging safety culture within the mining industry. However, it is difficult to envisage much support for the second recommendation, given the complexity of jurisdictions responsible for tailings dam regulation and widespread evidence that failures continue even with mature and experienced regulators. This will be discussed in more detail in a subsequent section of this Lecture.

3.3.6. Response of Mining Association of Canada (MAC)

The first edition of MAC’s Guide to the Management of Tailings Facilities was released in 1998 in response to a series of international tailings-related incidents that occurred in the 1990s, several involving Canadian mining companies. The overarching objective of this document was to help mining companies to implement safe and environmentally responsible management of tailings facilities. This was followed in 2003 with a companion document on “Developing an Operation, Maintenance, and Surveillance Manual for Tailings and Water Management Facilities.” Tailings management was further embedded in the “Towards Sustainable Mining” (TSM) initiative established in 2004, which provided clear guidance on governance issues. There has been strong external recognition that implementing the tailings management component of TSM is a best practice for tailings management. This was recognized in the report on the Mount Polley failure.

Following the Mount Polley incident, the Board of Directors of MAC initiated a review of the tailings management component of TSM which culminated in the revised Guide to the Management of Tailings Facilities (Third Edition), issued in November 2017 (MAC, 2017). This is an outstanding document particularly in its contribution to governance structure within companies which is necessary to underpin a commitment to safe design, construction, operation, and closure of tailings storage facilities.

MAC processes emphasize the value of conducting audits to verify commitment and effectiveness. There are the three levels that corporations aspire to. Numerous commitments are required to achieve each level. In the new edition, new guiding principles are introduced to include:

- i. Risk-based approaches
- ii. BAT and BAP for tailings management
- iii. The roles of independent review
- iv. Design and operating for closure
- v. Revised roles and responsibilities.

This new Guide provides an outstanding document to influence the organization and governance protocols needed to ensure safe tailings management from the conceptual stages through to closure.

3.3.7. Response of International Council on Mining and Metals (ICMM)

The ICMM and its predecessor organization, the ICME, has long recognized the significant role that mine tailings management plays in the overall risk profile of mining operations worldwide. This is of special significance since the ICMM represents the majority of the world’s largest mining and metals companies. In response to the crisis, ICMM undertook a global review of tailings storage facility standards, guidelines, and risk controls. The review was conducted by member company representatives, assisted by external experts. The focus was on corporate-level surface tailings management across the

membership, including standards, guidelines, risk controls, and governance and emergency preparedness related to the prevention of and response to sudden catastrophic failure of tailings storage facilities. The report arising from this important review and the recommendations based on its findings has been produced by Golder Associates (2016).

Before engaging in the review that concentrated on governance issues, the study team reflected on learning from recent high-profile failures and concluded:

"If one were to focus on these and other such case histories through consideration of a greater number of failure and investigation results over the last 20 or so years, and ask the question is there anything missing from existing standards and guidance documentation that if known and applied could have forestalled such events, then the answer might be as follows:

"Existing published guidance and standards documentation fully embrace the knowledge required to embrace such failures. The shortcoming lies not in the state of knowledge, but rather in the efficiency with which that knowledge is applied. Therefore, efforts moving forward should focus on improved implementation and verification of controls, rather than restatement of them."

Based on this justification, it was concluded that a higher level of governance and assurance is required for the effective implementation of good practice. To this end, the study focussed on the following core elements of good practice:

- i. Tailings management framework
- ii. Governance
- iii. Minimum requirements for design, construction, operation, decommissioning, and closure (including post-closure management).

Arising from the review of member company documents, five areas of improvement were identified and recommendations were made with respect to the following (see Report for details):

- i. The need for a tailings storage facility classification system based on the consequences of failure.
- ii. The need for a formal change management process related to material changes to the life of the facility plan.
- iii. The need for improved communication between the Engineer-of-Record and operator/owner.
- iv. Expanded utilization of formal risk assessment processes.
- v. The need for more independent review by suitably qualified and experienced professionals.

Additional details were provided regarding the recommended governance and tailings management framework, supported by the necessary assurance protocols.

Assisted by the Golder Associates (2016) study, ICMM also issued a Position Statement on Preventing Catastrophic Failure of Tailings Storage Facilities (ICMM, 2016). All members of ICMM are obliged to implement in their businesses the ten principles associated with the

ICMM Sustainable Development Framework. A number of these principles are of particular relevance to the need for preventing catastrophic failure of tailings storage facilities. The specific commitments related to an enhanced tailings governance framework require the following:

- i. Accountabilities, responsibilities, and associated competencies are defined to support appropriate identification and management of tailings storage facilities risk.
- ii. The financial and human resources needed to support continued tailings storage facilities management and governance are maintained throughout a facility's life cycle.
- iii. Risk management associated with tailings storage facilities, including risk identification, an appropriate control regime, and the verification of control performance.
- iv. Risks associated with potential changes are assessed, controlled, and communicated to avoid inadvertently compromising facility integrity.
- v. Processes are in place to recognize and respond to impending failure of facilities and mitigate the potential impacts arising from a potentially catastrophic failure.
- vi. Internal and external review and assurance processes are in place so that controls for facilities risks can be comprehensively assessed and continually improved.

It is of interest to note that members of ICMM are expected to implement the commitments required by this position statement by November 2018.

3.3.8. Commentary

Positive and productive responses to the crisis have been made by revisions of regulatory requirements at both the regional and national levels as well as recommendations for improved corporate practice, with emphasis on governance, as made by both MAC and ICMM. All are welcome. However, the question remains whether they are adequate to overcome the crisis.

3.4. The causes of catastrophic tailing incidents

3.4.1. Introduction

One cannot answer the question that asks whether the measures taken so far by the industry and the various regulators are sufficient to address the crisis and resolve it without understanding the causes of catastrophic tailings incidents.

I have been involved to various degrees in 15 public tailings incidents over the last 30 years, not all involving dam failures, but all involving safe tailings management. In the following, I have personally assessed the basic causes of each incident in terms of whether it was engineering, operations, or regulatory related. By engineering related, I mean related to the matters of design, construction, quality control, and quality assurance. By operations related, I mean deviations from an operation manual that would

guide such matters as water management, tailings placement, and care and maintenance and would usually be covered by an Operations, Maintenance, and Surveillance manual (OMS). By regulatory related, I mean decisions made, or not made, by a regulatory authority that contributed significantly to the incident that occurred. In some instances, it is not possible to discriminate clearly between one or the other basic cause, and in such cases, I nominate both (see Table 1).

It should be made clear that these attributions are personal judgments and are not to be confused with root causes that are more complicated to assess. I make no attribution of roles and responsibilities in the basic cause assessment. In most cases, a brief Internet search will provide supporting details and photographs. Therefore, in general, no detailed references are provided here. Where this is not the case, a brief commentary and extra referencing is provided. My involvement in these cases covers the range from participating in detailed forensic investigations through knowing enough from files managed by others to form an opinion.

3.4.2. Commentary

The first case, Tyrone, is mentioned in Martin & McRoberts (1999) who reference a more-detailed back analysis of the failure first presented by Carrier (1991), which is neither well-known nor readily accessible. It deserves wide-spread recognition because it highlights the limited understanding of the role of undrained analysis applied to tailings dam stability, which was extant at that time and continues to this day.

The second case, Ok Tedi, was not a failure of an operating tailings storage facility, but a failure during construction due to a large landslide that occurred in the eastern abutment of the dam. As a result, tailings storage concepts were abandoned in favor of riverine discharge solutions. This decision had disastrous environmental, social, and financial consequences, which are a matter of public record. Substantial litigation developed with respect to liability associated with the abandonment of the tailings storage site with conflicting expert reviews. Respected expert opinions varied from the view that the circumstances around the landslide were too complex, given the local conditions, for the hazard to be identified, to the alternative, that the studies were deficient. Fookes & Dale (1992) provide a summary of alternate views. It is not the intent here to favour one side or the other, but to draw attention to the fact that geological and geotechnical complexity in some instances may be too great to support site selection at all, which is not a comforting observation.

The third case, Stava, resulted in the loss of 269 lives, the destruction of two villages, and extensive property damage. This incident has received considerable attention in the literature and was the subject of extensive litigation. It will come as a surprise to many that I attribute the basic cause to regulatory decisions. The detailed support of this attribution is presented in Morgenstern (1996). This paper records that the mine was shut down in 1978, and the dams were abandoned, except for a pond in both dams to manage precipitation runoff. The local authorities encouraged new ownership, and mining recommenced in 1982 by an organization with, limited mining experience. Construction and

Table 1 - Basic causes of tailings incidents.

Name	Year	Place	Basic causes		
			Engineering	Operations	Regulators
Tyrone	1980	New Mexico, USA	✓		
Ok Tedi	1984	Papua New Guinea	✓		
Stava	1985	Italy			✓
Omai	1995	Guyana	✓		
Golden Cross	1995	New Zealand	✓		
Marcopper	1996	Philippines	✓		
El Porco	1996	Bolivia	✓		
Pinto Valley	1997	Arizona, USA	✓	✓	
Los Frailes	1998	Spain	✓		
Inez	2000	Kentucky, USA	✓	✓	
Kingston	2008	Tennessee, USA	✓		
Keephills	2008	Alberta, Canada	✓		
Obed	2013	Alberta, Canada		✓	✓
Mount Polley	2014	British Columbia, Canada	✓	✓	
Samarco/Fundão	2015	Minas Gerais, Brazil	✓	✓	

tailings operations were substantially modified by the new operator. In particular, mobile cyclone placement of tailings was abandoned in favor of single point discharge which allowed pond water to encroach on the beach of the dam, ultimately triggering static liquefaction. It appears that had the regulator not interfered in the fate of the facility, without prescribing operational restraints, the failure would not have occurred.

Not much information regarding the Pinto Valley failure is available in the public domain. It involved the static liquefaction of an old tailings facility that had been decommissioned in the 1970s while the second lift of a waste dump was being placed on it. From my limited familiarity with the files, both engineering and operational issues contributed to the incident.

The failure of the Inez coal tailings impoundment in Kentucky, USA, reflected technological and operational perspectives that appear peculiar to the coal industry in that part of the US. The technical challenges have been evaluated by a special committee established by the US National Research Council (Committee on Coal Waste Impoundments, 2002).

The Keephills incident is not well-known, primarily because it did not result in loss of containment. Instability of the wall of the impoundment occurred during dyke raising. Fortunately, the crest of the slide did not penetrate into the fluid contents of the pond. The slide was attributed to deficiencies in assessing the shear strength of the complex foundation conditions beneath the embankment.

The Obed incident is also associated with the coal industry. A water retaining dyke failed due to inadequacies in site-wide fluid management, indicating an operational Basic Cause. However, even though the operation was licensed as a mine, the retaining structure had not been reviewed by the dam safety regulator. This appears to have been a lapse in the approval of mine operations and hence a contribution from the regulator to the basic cause of failure.

3.4.3. Reflection

From a technical perspective, it is of interest to note that inadequate understanding of undrained failure mechanisms leading to static liquefaction with extreme consequences is a factor in about 50% of the cases. Inadequacies in site characterization, both geological and geotechnical, is a factor in about 40% of the cases. Regulatory practice, considered appropriate for its time and place, did not prevent these incidents. However, the most important finding is that the dominant cause of these failures arises from deficiencies in engineering practice associated with the spectrum of activities embraced by design, construction, quality control, quality assurance, and related matters. This is a very disconcerting finding.

There is an unwritten covenant in our professional practice with the assumption on the part of an operator that, given reasonable resources, and on the part of the regulator

that, given technical guidelines and a modicum of inspection, the engineering team can be relied upon to produce a tailings storage facility that will perform as intended. The experience summarized here leads to the conclusion that this covenant is broken.

The conclusions in the ICMM-sponsored study of tailings management guidelines (Golder Associates, 2016) and the recommendations embraced in the Tailings Governance Framework issued by ICMM (2016) are not adequate to resolve the crisis.

3.5. Toward zero failures

3.5.1. Introduction

The responsibility for improving the safety culture associated with the performance of tailings storage facilities through all cycles of their life resides primarily with the operators. While regulators also have a role, it is necessarily subordinate to the role of operators. Experience reveals that the advance of this safety culture to the goal of zero failures requires intrusion into not only the activities of the operator, but also into the activities of the engineer(s). However, this intrusion must not be so prescriptive that it needlessly limits the creative input from both the operator and the engineer. To this end, it is recommended for any specific project that the operator be required to develop, for regulatory approval and subsequent execution, a tailings management system for Performance-Based, Risk-Informed, Safe Design, Construction, Operation, and Closure of the proposed tailings storage facility (PBRISD). Many single elements combined in PBRISD have been identified before, but the required integration presented in the following is perceived as necessary to impose more rigorous direction, supported by critical levels of review at various stages of the process.

3.5.2. Outline of PBRISD

For convenience, the organization of PBRISD is broken down into various stages of the life cycle of the project. Actual projects will develop the proposed system with reference to their own specific details.

3.5.2.1. Stage 1: (Conceptual)

This stage is associated with site and technology selections that generally are intended for application for approval by a regulatory process. The following elements are part of this stage:

- i. Qualified Operator (QO). Any proponent must establish itself as a QO. This is achieved by declaring that its safe management system will be compatible with the MAC 2017 Guide. In addition to prescribing to this excellent guide to the management of tailings facilities, the establishment of the following three critical positions becomes a commitment: i) Accountable Executive Officer, ii) Responsible Person(s), and iii) Engineer-of-Record.

- ii. Establish Independent Review Board. This will require creating a risk-based classification of facilities to provide guidance on the extent to which external review boards are required. Clearly there are instances where, either by past experience or by limited risk, no external independent review is necessary. At the other extreme, a three- to four-person board is required. Guidance is also required to assist the QO in forming such a board. Examples of terms of references are needed as well as a discussion on dealing with confidential matters, while also assessing safety issues that should be available in the public domain. Hence, reporting structures for boards need summarizing as do legal/commercial issues such as indemnification of board members for potential legal actions beyond their remit.
- iii. Uncertainty Assessment. It should be recognized at this early stage that safe design and operation relies on a large number of models (*e.g.*, the geological model, the hydrogeological model, the geochemical model, the geomechanical model, the stability model). All of these models possess uncertainties which either are addressed or become irrelevant with time. A first assessment of all uncertainties should be conducted in this stage for all options under consideration.
- iv. Potential Problems Analysis (PPA). The first formal risk analysis for all options under consideration should be a PPA which is a systematic method for determining what could go wrong in a plan under development. It is not anticipated that all issues would be addressed in Stage 1. However, the analysis might influence the recommendations arising from Stage 1 and residual concerns would be addressed in Stage 2.
- v. Multiple Account Analysis (MAA). The options for tailings technology and site selection considered in Stage 1 and recommendations arising from the assessments should be supported by an MAA. This is a structured decision-making process that makes transparent how both corporate and other stakeholder values have been considered in the assessment process. It is of considerable value in both documenting process as well as promoting trust. The MAA procedure has long been advocated by the federal regulators in Canada and is also outlined in MAC (2017).

3.5.2.2. Stage 2: (Feasibility)

This stage is associated with advancing the design of the selected option to a level both appropriate for making a financial commitment to proceed and to submit a design in sufficient detail to receive approval from the dam safety regulator. The following elements are part of this stage:

- i. Engineer-of-Record (EoR). The position of EoR is widely recognized as an integral part of the tailings management team dedicated to safety performance of the facility. The role of the EoR is to verify that the

facility has been designed in accordance with performance objectives and is supported by applicable guidelines, standards, and regulatory requirements. When constructed, it will perform, throughout the life cycle, in accordance with the design intent, performance objectives, applicable guidelines, standards, and regulatory requirements. The EoR is generally perceived to be a person and not a firm. While the functions of the EoR are important, there is still some debate in practice as to how these functions are best fulfilled, particularly if the QO has substantial in-house geotechnical and construction capability, as well as increasingly automated instrumentation and interpretation capacity. This is made more complex when the life of the facility is long and change of the EoR is inevitable. Guidance is required to assist the QO in evaluating the best way to fulfill the requirements of the EoR.

- ii. Designer. The designer selected for Stage 2 has a crucial role in all aspects of this stage. Some regional procurement practice places a strong emphasis on competitive costs which can result in breaking the design into small segments for either economic or other perceived management objectives. The QO needs guidance on procurement policy and the risks that might be generated by multiplying design interfaces.
- iii. Design Basis Memorandum (DBM). The DBM is the critical document that supports all design criteria and related methodology. It is subject to change based on evolving experience and methodologies. Documentation of change to the DBM must be formalized in a comprehensive manner. While the review board will participate throughout this stage, it is expected that review of the DBM and related matters will receive special attention. It is expected that all geotechnical design will adopt the observational method where possible. This is a precautionary-based design, to verify that no significant departures from design assumption have been identified. It requires prior identification of practical mitigation measures in the event that observations reveal that they are prudent or necessary. It is also expected that geotechnical design, at least for the more challenging undertakings, will increasingly utilize performance-based design. With advances in performance modeling, monitoring, and interpretation in a timely manner, it is now practical to move in this direction. The outcome is improved safety assessment and increased opportunities for optimization. Morgenstern (2017) discusses the merits of this transformation in more detail.
- iv. Risk Assessment. Risk assessments will be carried out as the schedule for Stage 2 dictates. For planning purposes, risk assessments at 30% and 70% completion should be in the development plan. The PFMA methodology is recommended. Some guidance is provided

- in the MAC 2017 Guide, but additional documentation may be warranted for the QO.
- v. Quality Management. Detailed quality management plans will be developed distinguishing between Quality Control (QC) and Quality Assurance (QA). When construction is performed by the mine itself, ambiguities often arise. It is necessary to emphasize the independence of QA and, if conflicts arise with QC, to have resolutions at a senior level to ensure that production concerns do not overwhelm quality concerns. QA should also be responsible for the construction report which is an indispensable document, both for supporting the EoR requirements as well as constituting a basic resource to inform future long-term safety assessments.
 - vi. Documentation. Experience with recent failure investigations highlights the need to have complete as-built data and other records compiled, preferably on a GIS platform, and accessible so that a technical audit could be conducted at any time. This is a valuable insurance document for all involved in the project and merits dedicated planning and support.

3.5.2.3. Stage 3: (Construction and operations)

Both construction and operations tend to overlap in the evolution of tailings storage facilities. Managing the construction follows naturally from the processes that evolved in Stage 2. However, additional considerations are needed to guide safe operations.

- i. Operations. Both safe construction and safe operation are guided by an Operation, Maintenance, and Surveillance Manual (OMS). This document requires critical reviews from the review board and periodic updating. The MAC 2017 Guide also provides valuable guidance on the development of this document.

3.5.2.4. Stage 4: (Closure implementation)

Modern project planning recognizes the need to integrate mine planning, tailings planning, water planning, and closure planning at the outset. It is assumed here that in PBRISD closure planning will be considered in all of the previous stages, at increasing levels of detail with time. From a geotechnical perspective, the primary concern is with the physical and chemical integrity of the ultimate landforms and release fluids. Closure design should recognize that the construction as-built record constitutes a basic reference for landform design under closure conditions. The evolution of closure design should emphasize the need for a new DBM to identify closure design criteria and methodology for the physical and chemical aspects of the closure landscape. Ongoing safety assessments must be able to rely on the as-built record as reliable to avoid the circumstances that occurred at Oroville Dam.

3.6. Guidance

The design, construction, operation, and closure of modern tailings facilities to acceptable standards of safety and environmental impact is a complex undertaking. Both experience and system analysis indicate clearly that it is not possible to meet acceptable standards by regulations alone. It is the primary responsibility of the proponent to put forward an acceptable waste management plan that meets these standards. The evolving crisis related to trust and confidence, discussed here, has also revealed a high rate of technical deficiencies as a significant factor in the failures that have been documented. It is tempting to conclude that increased prescriptive measures controlling the engineering works are required. However, the intrinsic complexity and diversity of the undertakings reduces the reliability of this perspective. Instead, the underlying principle for the tailings management system advocated here (PBRISD) is accountability. This is achieved by multiple layers of review, recurrent risk assessment, and performance-based validation from construction through closure.

The regulator also has a vital role. It is the responsibility of the regulator to review the proposed waste management plan and indicate how it is to be validated. This will involve some combination of inspections concentrating on quantified performance objectives, receiving review board reports, and other measures deemed necessary. The regulator is also the custodian of prescribed regional practice. For example, the regulator in Chile may continue to ban upstream construction even though technical arguments can be advanced that they can be designed and operated in a safe manner.

3.7. Recommendations

In order to turn the system recommended here into a reality, it is necessary to expand the skeleton outline into a guidance document that would help individual operators in developing a tailings management system for their specific operations based on PBRISD. The principles involved in PBRISD are entirely consistent with the ten principles that are the foundation of ICMM's Sustainable Development Framework. In addition, supporting the adoption of PBRISD can be regarded as a natural extension of the action already taken by ICMM in their 2016 Position Statement.

This Lecture concludes with the recommendation that ICMM support the tailings management system based on PBRISD, as outlined here, and fund the development and publication of a guidance document that would facilitate its adoption in mining practice.

4. Concluding Remarks

This Lecture has explored the evolution in practice of a safety culture in several important aspects of geotechnical practice. The range covers examples of success to examples of failure related to public aspects of geotechnical practice.

The example of success is the Slope Safety System in Hong Kong, to which Victor de Mello contributed in its early development.

The intermediate example relates to water dam safety where the recent Oroville Dam incident in California has exposed disconcerting practice in dam safety evaluation. Some of the learnings from this incident are presented and recommendations have been made to improve practice in water dams safety assessment.

Currently, the weakest safety culture is associated with tailings dams. Here, several high-profile failures have, in recent years, created a crisis due to loss of trust and confidence in the design, construction, and operation of such facilities. The Lecture reveals that this appears to be justified, particularly due to weak engineering in many instances (design, construction, QC, QA). Recommendations are made, primarily to operators, as to how to develop an improved tailings management system to maximize reliable performance.

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