Long Term Risk of Releasing Potentially Acid Producing Waste Due to Tailings Dam Failure

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Abstract
Large tailings dams built to contain mining waste, among the largest dams and structures in the world, must stand in perpetuity. If a catastrophic release of tailings were to occur, it could lead to long term environmental damage with huge cleanup costs. Tailings dams have failed at a rate that is significantly higher than the failure rate for water supply reservoir dams. The causes for the higher incidence of tailings dam failures between tailings and water supply reservoir dams are probably shaped by two factors: (1) the ability to use construction types for tailings dams that are more susceptible to failure; and, (2) the fact that tailings dams are most often constructed in sequential 'lifts' over several years that make quality control more challenging relative to water supply dams that are constructed all at once.

Technology and science has limits, and there are significant economic incentives to make present day decisions about risk less, rather than more, conservative about the magnitude of these risks. In looking at the long term risk from tailings impoundments to other resources, policy makers should view the risks from a conservative probabilistic perspective rather than relying on assumptions about specific hazards that are likely flawed.

Long Term Tailings Dam Stability
Tailings impoundments have been around for about a century.[2] The construction and care of a tailings dam is a relatively new phenomenon to society and to mining, which historically disposed of its waste in the most convenient way. Tailings dams differ from water supply reservoir dams in two significant ways – dam design life, and dam construction design.

First, unlike a dam built for impounding water, which can ultimately be drained if the structural integrity becomes questionable, a tailings dam must be built to stand in perpetuity. This consideration should impose additional design requirements, especially with regard to the seismic and hydrologic events the dam might experience. These issues will be addressed in more detail in this paper.

Second, while water supply dams are all of the downstream-type construction, the construction of tailings dam can be either (1) downstream; (2) centerline; (3) upstream; or, (4) a combination of any of the previous methods.

Tailings Dam Failure Incidents
Even with an obvious requirement for long term stability, since 1970, the number of tailings dam failures has significantly exceeded the failures for dams used for water supply. See Figure 1.

There are more than 3500 tailings dams located around the world (Davies, M.P. and T.E. Martin, 2000). There are between 25,420 and 48,000 large dams worldwide[3] (World Commission on Large Dams, 2000, Annex V Dams, Water and Energy – A Statistical Profile, Table V.5 Summary of regional statistics on large dams). Tailings dam failures have occurred more frequently than water supply dam failures (Davies, M.P., 2002, p. 32).

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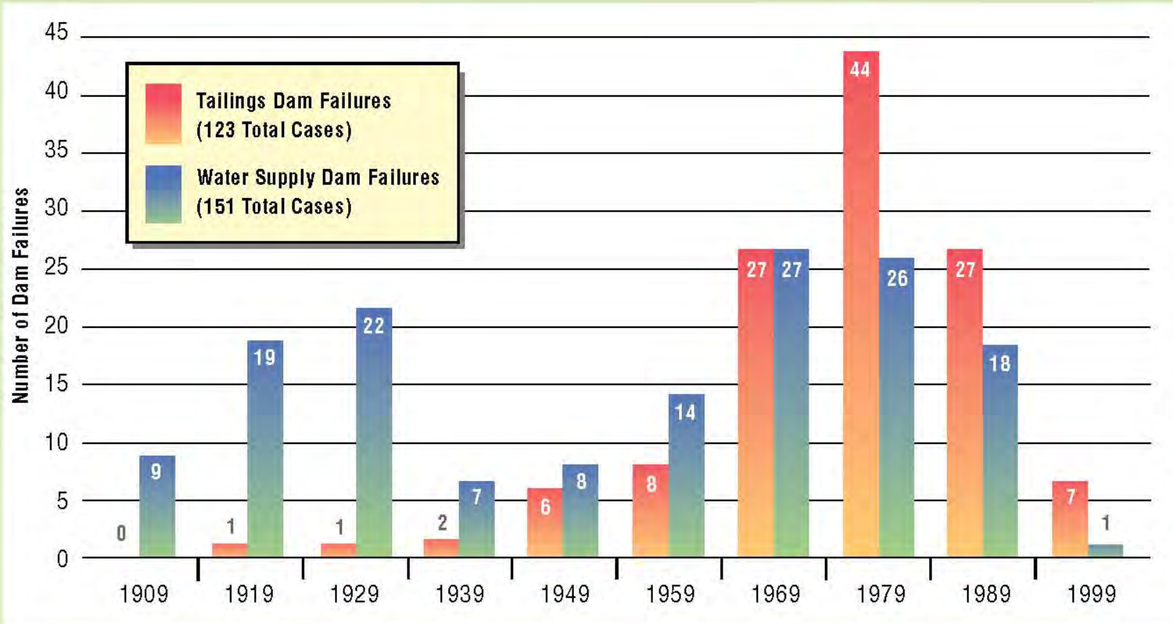
[2] See MMSD, 2002, for a short summary of the history of modern mining.
[3] Data from 1998. The potential variation in the total number is due in large part to the unreliability in data from China, the country with the largest number of dams in world.



HOW SAFE ARE TAILINGS DAMS?

While it appears that the mining industry has the knowledge to design dams safely, can it be said that all dams are built to the same standards, with state-of-the art technology and management? Some are better than others, and failures have occurred. Several recent studies have been conducted to compile data on tailings dam failures, isolate the causes of these failures and identify trends (USCOLD, 1994; UNEP, 1996). No single legislative body, however, records tailings dam statistics. Furthermore, the data do not allow comparisons between the number of tailings dam failures and the total number of tailings dams built in any given area or time period.

However, comparisons have been made between tailings dam failures and incidents at hydroelectric and water-retaining structures (ICOLD 1995b). Although the database is incomplete, some convincing trends have emerged. The above chart shows a plot of the total number of failures reported for all countries in 10-year increments for both tailing dams and water supply dams. Before the 1940s, there were very few reported failures of tailings dams, either because many of the existing dams were not documented, or because the total number of failures was small. From the 1940s to the 1970s, the number of failures for both tailings dams and water supply dams increased substantially. The rise in the number of failures in the 1950s to 1960s may have been due to the increasing size and weight of earthmoving equipment. This trend peaks in the late 1960s for water supply dams, and in the 1970s for tailings dams. The overall behaviour of the two structure types is, in general terms, very similar.

Figure 1. Tailings Dam Failures (UNEP, 1998)

This is probably due to two factors: (1) the ability to use construction types for tailings dams that are more susceptible to failure; and, (2) the fact that tailings dams are most often constructed in sequential ‘lifts’ over several years that make quality control more challenging relative to water supply dams that are constructed all at once.

Because of the alarmingly high number of tailings dam failures, the International Commission on Large Dams (ICOLD) convened several studies to investigate tailings dam failures.

> *"Satellite imagery has led us to the realisation that tailings impoundments are probably the largest man-made structures on earth. Their safety, for the protection of life, the environment and property,*

is an essential need in today's mining operations. These factors, and the relatively poor safety record revealed by the numbers of failures in tailings dams, have led to an increasing awareness of the need for enhanced safety provisions in the design and operation of tailings dams. The mining industry has a less than perfect record when tailings dam failures are reviewed." (ICOLD, 2001, p. 15)

"Unfortunately the number of major incidents continues at an average of more than one a year. During the last 6 years the rate has been two per year." (ICOLD, 2001, p. 8)

In the 10 years since the ICOLD 2001 report the failure rate of tailings dams has remained at roughly one failure every 8 months (i.e. three failures every two years).[4] See Figure 2. Over a 10,000 year lifespan (a conservative estimate for how long these structures will need to maintain integrity) this implies a significant and disproportionate chance of failure for a tailings dam. One explanation might be that we are still experiencing the effects of old technology and practices, but it has been 15 years since the International Commission on Large Dams initiated a major effort to investigate tailings dams and change construction and operational practices, and the rate of tailings dam failures has remained relatively constant.

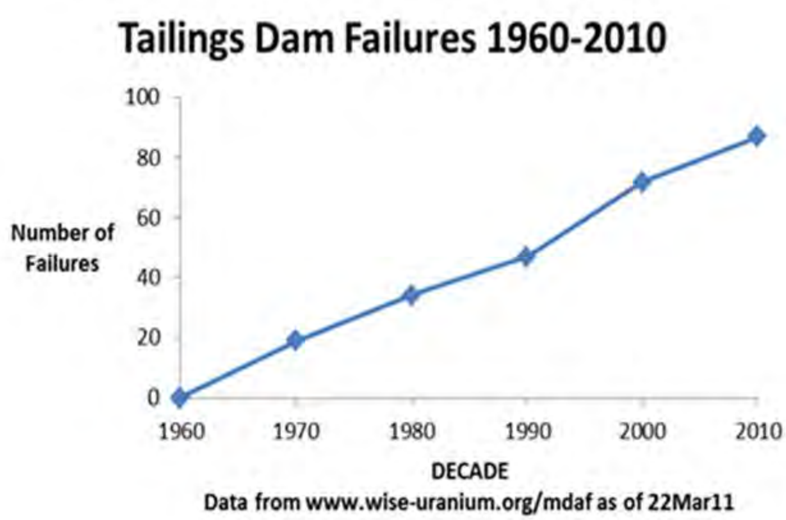


Figure 2. Tailings Dam Failures 1960 - 2010

These dam failures are not limited to old technology or to countries with scant regulation. Previous research pointed out that most tailings dam failures occur at operating mines, and that 39% of the tailings dam failures worldwide occur in the United States, significantly more than in any other country (Rico, et. al., 2008a, p. 848).

Why Tailings Dams Fail

Some of the long-term failure mechanisms for tailings dams include cumulative damage (e.g. internal dam erosion and multiple earthquake events), geologic hazards (landslides, etc.), static load induced liquefaction,[5] and changing weather patterns.

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[4] Data from http://www.wise-uranium.org/mdaf.html "Chronology of major tailings dam failures" as of March 22, 2011

[5] Static liquefaction refers to the loss of strength in saturated material due to the buildup of pore water pressures unrelated to "dynamic" forces (most typically earthquakes).

The three leading causes for tailings dam incidents[6] are ‘overtopping’, ‘slope stability’, and ‘earthquakes’.[7] Designing for both overtopping and earthquakes requires a prediction of the largest hydrologic or earthquake “event” the tailings dam will see during its lifetime, and in each of these instances the required lifetime is almost always perpetuity. Better data, better prediction methods, and following conservative guidelines for assuming the worst-probable event are needed to remedy these problems. The time periods we are concerned with are many millennia, but in the best case data collection is limited to decades.

Assumptions must be made as to magnitude of hydrologic and seismic “maximum” events. There is a well understood tendency to make assumptions that favor short-term economic situations, and to assume that present technology can and will minimize the long-term risks associated with the design, operation, and long-term closure of tailings facilities.[8] The statistics of tailings dam failures strongly suggest that these issues have still yet to be adequately addressed.

Dam incidents in the ‘slope stability’, ‘foundation’, and ‘structural’ categories can be largely attributed to engineering design or construction failures. Better design and construction practices, and adopting larger margins of safety in the designs, are needed to tackle these problems.

When Tailings Dams Fail

Findings from research associated with tailings dam failures show estimates can be made both for the volume of tailings that could be released from a tailings dam, and the distance downstream/downgradient from the failure the waste could be expected to move.[9]

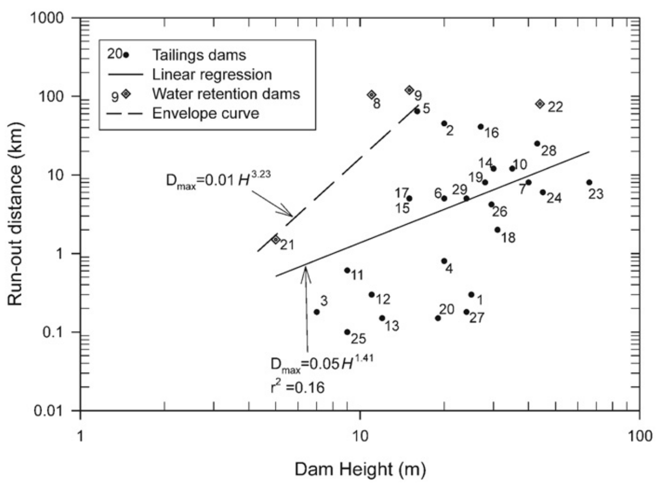

Figure 3. Dam Height v. Runout Distance (Rico, 2008b, p.81)

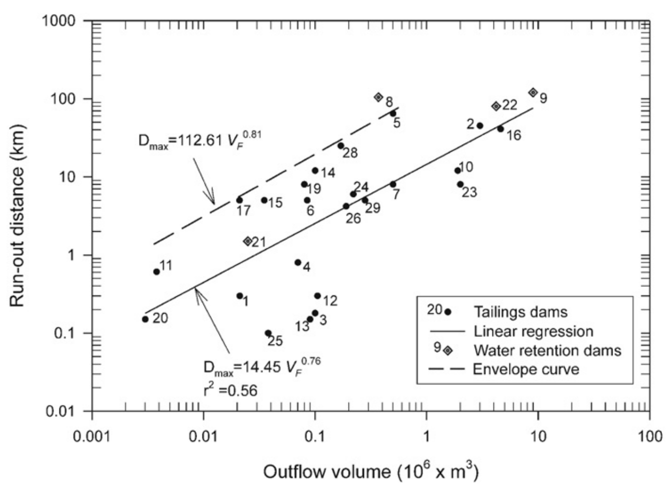

Figure 4. Dam Volume v. Runout Distance (Rico, 2008b, p.82)

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[6] A “dam incident” is an unexpected event that occurs to a tailings dam that poses a threat to dam safety or the environment and requires rapid response to avoid a likely dam failure. (ICOLD, 2006, p. 63) Note: The dam incidents in Figure 9, ICOLD, 2001, include “dam failures” – an event resulting in the escape of tailings and/or water from the tailings dam.

[7] ICOLD, 2001, (p. 15, Figure 9) This figure indicates that the leading causes for incidents are slope instability, earthquake and overtopping: particularly so for dams constructed by the upstream method.

[8] One leading tailings dam design expert has noted: *“As time goes on, the largest event to have been experienced can always be exceeded but can never be made smaller.” (European Commission, 2001, "Stability Aspects of Long-Term closure for Sulfide Tailings", Steven G. Vick)*

[9] This research was initiated largely in response to the tailings dam failure at Los Frailes, near Seville. Spain, in 1998

The researchers that developed these graphs in Figure 3 and Figure 4 noted that:

> *"… key hydrological parameters associated with dam failures (e.g., outflow volume, peak discharge, mine waste run-out distance) can be estimated from pre-failure physical characteristics of the dam (dam height, reservoir volume, etc.), based on reported historic dam failures." (Rico, 2008b, p. 80)*[10]

> *"The reports on tailings dam failures are incomplete and heavily biased. There is no (complete) worldwide database of all historical failures. ... The majority of tailings dam incidents remain unreported, especially in developing countries. ... To date, 250 cases of tailings dam failures in the world have been compiled." (Rico, 2008b, p.80)*

In spite of a basic understanding of the mechanisms that cause tailings dam failures, and a convincing collection of empirical data on the impact of these failures, we have continued to see tailings dams fail at a relatively constant rate over the last five decades.

Regulatory Framework

The design standards for most tailings dams are determined by state dam safety agencies. Although there are hazard classification and earthquake analysis guidelines for dams published by the Federal Emergency Management Agency (FEMA), these guidelines are oriented toward water reservoirs, and do not specifically address tailings dams.[11]

Closely following the FEMA recommendations are guidelines for coal tailings dams, but these guidelines do not address the much larger and potentially more damaging metal-mine tailings dams.[12] There are no definitive federal regulations governing the construction and operation of metal-mine tailings dams, and only minimal federal involvement in the design of metal-mine tailings dams, usually only when there is a lack of state oversight.[13]

The standards that do exist often lack specificity, and implementation of the standards depend in large part on the professional judgment and experience of company consultants and government regulators. While this builds regulatory and site-specific flexibility into permits for tailings dams, it also means that critical specifications are often left for company consultants to define, and regulators to approve.

Hydrology-Related Risk

The water storage capacity of a tailings dam and the water release capacity, via a spillway, is governed by the choice of the maximum hydrologic event (storm and/or snow melt) that the facility will experience over its life. Guidance for determination of the design flood event to be used for mine closure has been evolving, and is still in flux. In 1995, the International Commission on Large Dams suggested that the Probable Maximum Flood be used as the design standard, but left the possibility of utilizing a lesser event open to consideration.

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[10] It is somewhat unsettling to realize that there is more than enough data on actual tailings dam failures to establish the empirical relationships presented in these graphs.

[11] Federal Emergency Management Agency (FEMA), 2005, Federal Guidelines for Dam Safety, Earthquake Analyses and Design of Dams, FEMA 65, U.S. Department of Homeland Security, FEMA, Washington, DC.; and, Federal Emergency Management Agency (FEMA), 2004, Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams, FEMA 333, Interagency Committee on Dam Safety (ICODS), Washington, DC

[12] Mine Safety and Health Administration (MSHA), 2009, Engineering and Design Manual, Coal Refuse Disposal Facilities, prepared by D'Appolonia Engineering, May 2009

[13] For example the Army Corps of Engineers, the US Forest Service, or Bureau of Land Management might be involved in tailings dam design if there is no state oversight of dam design for a mining project that requires a federal permit.

“As in the case for the operating dam, hydrological criteria for safety of the dam after closure must be carefully considered. The Probable Maximum Flood should be considered for this evaluation although the 100-year design flood is often accepted for this purpose.” (ICOLD, 1995, p. 81)

Six years later the International Commission on Large Dams took a stronger stand, recommending that the Probable Maximum Flood, not a lesser event, be used as the design event for mine closure.

"All impoundments and their retaining dams need to be able to accommodate extreme hydrologic events, up to the Probable Maximum Flood." (ICOLD, 2001, p. 31)

Yet even today the design hydrologic event for dam construction is not required to be the Probable Maximum Flood in many regulatory jurisdictions. The choice of a lesser event would make dam construction less expensive. In the absence of a regulatory requirement there can be economic pressure to consider less stringent options.

Meteorological events led to most of the tailings dam failures, with seismic events triggering the second most failures (Rico, et. al., 2008a, p. 846). Upstream-type dam construction was involved with more of these incidents than any other type (Rico, et. al., 2008a, p. 849).

Seismic Safety Standards for Tailings Dams

There is a risk that a large earthquake might cause catastrophic failure of a tailings dam, with the release of a large amount of tailings, and could lead to long term environmental damage with huge cleanup costs. The probability of such a catastrophic failure is low, but the consequences should it occur are very high. Cleanup costs are often borne by the public, and if the tailings are not cleaned up, then the long term environmental and social costs would also be borne by the public.

When planning a dam, the design seismic event is often described with two terms, the Operating Basis Earthquake and the Maximum Design Earthquake. The Operating Basis Earthquake (OBE) represents the ground motions or fault movements from an earthquake considered to have a reasonable probability of occurring during the functional life-time of the project (Alaska Department of Natural Resources, 2005, p. 6-6). The Maximum Design Earthquake (MDE) represents the ground motions or fault movements from the most severe earthquake considered at the site, relative to the acceptable consequences of damage in terms of life and property (Alaska Department of Natural Resources, 2005, p. 6-6, 6-7). Since a tailings dam must stand in perpetuity, the Operating Basis Earthquake should be equivalent to the Maximum Design Earthquake.

The estimated largest earthquake that could occur at any given location is called the Maximum Credible Earthquake. The Maximum Credible Earthquake (MCE) is defined as the greatest earthquake that reasonably could be generated by a specific seismic source, based on seismological and geologic evidence and interpretations (Alaska Department of Natural Resources, 2005, p. 6-6). The Maximum Credible Earthquake is often associated with a recurrence interval of 10,000 years.[14]

Existing regulatory guidelines for the choice of the location of the Maximum Design Earthquake or Maximum Credible Earthquake, which do not specifically consider metal-mine tailings dams, leave the final location of these seismic events for project-related experts to determine. For most projects engineering experts from consulting firms, hired by mining companies, use deterministic or probabilistic methods to select the location and size of the Maximum Credible Earthquake and/or Maximum Design

[14] Large Dams the First Structures Designed Systematically Against Earthquakes, Martin Wieland, ICOLD, The 14th World Conference on Earthquake Engineering, Beijing, China, October 12-17, 2008

Earthquake. This is a complex process, and regulators are typically involved only at an approval level, not in the detailed analysis.

Engineering consultants are not experts on determining the amount of risk that is appropriate in determining public policy. Public policy determinations on risk are typically reflected in regulatory requirements, but for the determination of the size of the Maximum Credible Earthquake and/or Maximum Design Earthquake for a tailings dam there is a great deal of regulatory flexibility, often exercised by one regulator.

For tailings dams the Maximum Design Earthquake is a key variable, since the facility (dam) must provide perpetual containment for the waste. The choice of the MDE should reflect the largest event that the dam would be expected to experience during its functional lifetime, and survive the shaking produced by this event. Because tailings dams are structures that must impound waste with chemical properties and/or physical properties that pose long term risk to the public and the environment, assumptions related to critical design parameters for these structures should be the most conservative in order to protect public interests and public safety.

The choice of the Maximum Design Earthquake for a tailings dam becomes important not only from the perspective of determining the largest seismic event that dam can withstand and still hold back the material it is impounding, but also because there is a direct correlation between the size of the MDE and the cost of constructing the dam – the larger the MDE, the greater the cost of the dam. Tailings dam construction costs generally run from tens to hundreds of millions of dollars. Tailings dam construction cost is one of several significant factors in determining the cost of mining, and the competiveness of the mine in the international markets.[15]

The choice of the Maximum Credible Earthquake as the Maximum Design Earthquake for a tailings dam is an appropriately conservative choice for the design seismic event. For most structures, including the design of buildings and other structures that are designed with finite lifetimes, the choice of a Maximum Design Earthquake is often one with a recurrence interval significantly less than that of the Maximum Credible Earthquake, since these structures will not be used indefinitely.

Tailings dams, however, require a very conservative choice of design event. Once these structures are built, it is not economically or environmentally viable to move the waste that is impounded behind the dam. The dam must hold this waste safely in perpetuity. We don’t know how long ‘perpetuity’ means, but 10,000 years (e.g. the approximate time since the last ice age) is a minimum approximation.

> *"According to the current ICOLD guidelines, large dams have to be able to withstand the effects of the so-called maximum credible earthquake (MCE). This is the strongest ground motion that could occur at a dam site. In practice, the MCE is considered to have a return period of several thousand years (typically 10’000 years in countries of moderate to low seismicity)." (Wieland, ICOLD, 2001)*

The unintended release of the waste behind a tailings dam imposes real costs on society. There is a direct economic cost associated with cleaning up the waste that would escape from a failed impoundment, which can run into the hundreds of millions of dollars.[16] If there is no cleanup the long term environmental costs will be borne by local communities, both natural and human, and could be even larger than the direct cleanup costs.

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[15] Other significant cost factors for a mine include the construction of the mine and mill facilities, power generation, and operating costs (labor, materials, fuel, etc.).

[16] For example the Los Frailes dam break (near Seville, Spain), April 1998. As of August 2002 the cleanup cost was 276 million Euros (El País/El Mundo, August 3, 2002)

Tailings dams, which must impound the waste behind the dam in perpetuity, should use the Maximum Credible Earthquake as the Maximum Design Earthquake. However, because cost is a significant factor in the economic viability of mining projects, the Maximum Credible Earthquake is considered, but often not required as the Maximum Design Earthquake for tailings dams in many regulatory jurisdictions.[17]

Once the size of the design seismic event has been determined, it must be given a location. The further away the tailings dam is from the location of the earthquake, the less energy the tailings dam will need to withstand in order to maintain its structural integrity. The closer the location of the earthquake to the tailings dam, the higher the cost of building the dam, because the closer the earthquake the more energy the dam will have to withstand.

Seismologists know that there are many active faults that have not been mapped or have been mapped inaccurately, that some faults believed to be inactive may actually be active, and that there are many inactive faults that may become active again.[18] Because of these considerations, probabilistic methods are the more conservative way to determine the magnitude of a Maximum Credible Earthquake for dam analysis.

For tailings dams the most conservative choice for the location of the Maximum Design Earthquake would be what is sometimes referred to as a 'floating earthquake' on an undiscovered fault that passes very near the site of the dam. This is a way of recognizing that we do not know the present, future, and even the past locations of significant faulting, and associated earthquakes (National Research Council, 1985, pp. 67-68). The conservative choice for a Maximum Design Earthquake would be a Maximum Credible Earthquake that ruptures the ground surface on which the dam is built.

Case Study: Seismic Risk in the Area of the Pebble Mine

Alaska dams fall into one of three classes:

(1) Class I - Probable loss of one or more lives
(2) Class II - No loss of life expected, although a significant danger to public health may exist
(3) Class III - Insignificant danger to public health
(Alaska Department of Natural Resources, 2005, Section 2.4 Hazard Potential Classification, Table 2-1. Hazard Potential Classification Summary)

The Alaska dam classification system is designed primarily for water retention dams. Tailings dams are not specifically mentioned in the Alaska regulations, yet tailings dams are the largest dam structures in the state. From a classification standpoint the main difference between a Class I and Class II dam is essentially that people are directly at risk below a Class I dam, but there are no human habitations directly below a Class II dam. However, from a performance standpoint the most significant difference in dam safety requirements between a Class I and Class II dam is the size of the earthquake the dam is required to withstand (see Alaska Department of Natural Resources, 2005, Section 6.3.2 Design Earthquake Levels, T able 6-2. Operating-and Safety-Level Seismic Hazard Risk).[19] Class II dams must withstand seismic

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[17] For example, the State of Alaska does not require the use of the Maximum Credible Earthquake for tailings dam design. (Alaska Department of Natural Resources, 2005, Table 6-2. Operating- and Safety-Level Seismic Hazard Risk)

[18] Faults, and the corresponding earthquakes, are most often very deep structures. The major source of the energy associated with an earthquake is usually located a significant distance below the earth's surface.

[19] This points to a fundamental flaw in the Alaska Dam Classification Seismic Stability Regulations, where large tailings dams could be regulated as Class II dams with significantly less seismic safety requirements than Class I, even though they are the largest dams in Alaska, and have an infinite lifetime. The author has discussed this situation with officials in the Alaska Department of Natural Resources, and while sympathetic they point to the difficulty in changing regulations, and the flexibility of the State to require some dams to be Class I. However,

events with return periods of 1,000 – 2,500 years, and Class I dams 2,500 years to the Maximum Credible Earthquake (Alaska Department of Natural Resources, 2005, Table 6-2). It is not mandatory to use the Maximum Credible Earthquake as the Maximum Design Earthquake for a Class I dam.

Pebble consultants assumed the Lake Clark Fault is 18 miles from the minesite, and using this deterministic location ignored the risks from unknown or poorly-mapped faults, and could also lead to underestimating the amount of energy that could impact a tailings dam at the Pebble minesite.[20] Pebble consultants used calculations for maximum horizontal acceleration are based on a 1-in-5000 year earthquake, not the 1-in-10,000 year event recommended by the International Commission on Large Dams (Knight Piesold Ltd., 2006, Section 3.2.2 Seismic Hazard Analyses, Table 3.1). The choice for the magnitude of the Maximum Credible Earthquake for Pebble is not as conservative, as that recommend by International Commission on Large Dams. Because a return period of 5000 years has been chosen instead of the 10,000 years recommended by ICOLD, it is unlikely that the horizontal acceleration of the 1 in 3,000 – 5,000 year event (0.3 g – Knight Piesold Ltd., 2006, Section 3.2.2 Seismic Hazard Analyses, Table 3.1) is as large as that of the horizontal acceleration for a 1 in 10,000 year event would be.

Using a seismic event with a return period of 5000 years implies that the dam will experience an earthquake of this magnitude sometime during the 5000 year period. Over 10,000 years the dam could experience an earthquake of this size twice. Using an earthquake with a return period of 10,000 years would probably mean that the dam would have to be designed to withstand more energy and longer shaking. This means more expense in building the dam, but it would make the dam less likely to partially or fully fail over the long term.

Another factor affecting the seismic design is the location of the Maximum Credible Earthquake. Pebble consultants chose not to locate its MCE as a floating earthquake near the dam site, but picked a location for the MCE deterministically18 miles away (Knight Piesold Ltd., 2006, Section 3.2.2 Seismic Hazard Analyses, Table 3.2). Fault locations in this area are imprecise. The potential for an earthquake occurring in a different place than expected is the major downfall of this deterministic method of risk estimation, particularly in places, like the Pebble area, where faults have been poorly mapped.

It is very possible that an active fault could be located closer to the mine-site than assumed by Pebble consultants. Pebble consultants made statements assuring that they have done "extensive research" into seismic potential in the area, but the lack of fieldwork or peer reviewed research on these faults suggests this research may not be adequate. The choice of the location for the Maximum Design Earthquake, on the Lake Clark Fault 18 miles from the mine-site may be inaccurate, which could lead to a dramatic underestimation the peak ground acceleration that could impact a tailings dam at the Pebble mine-site (Knight Piesold Ltd., 2006, Section 3.2.2 Seismic Hazard Analyses, Table 3.2). In fact, there was a small earthquake on July 12, 2007, located approximately 20 miles from the Pebble location. See Figure 5. This earthquake had a preliminary magnitude of 4.4 and was located at a depth of about 6.2 km (approximately 4 miles) (Alaska Earthquake Information Center, Information Release, as of 2May11). This earthquake was not located on a known fault, but it is potentially in line with one of the splays of the Lake Clark Fault. This type of earthquake suggests either the extension of a known fault or an unmapped fault, either of which may pass closer to the Pebble site than the current estimate.

Picking the Maximum Credible Earthquake using a deterministic method when the location of the fault is uncertain is insufficiently conservative to protect public safety over the life of the tailings dam. Lacking

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some large Alaska tailings dams have been classified as Class II in the past (Red Dog, although it is voluntarily being upgraded to Class I), and the possibility for this happen again still unnecessarily exits.

[20] Table 3.2, Section 3.2.2 Seismic Hazard Analyses, Knight Piesold Ltd., 2006, shows the deterministic locations and associated magnitudes of the Maximum Design Earthquakes analyzed for Pebble in 2006. A probabilistic floating earthquake is not included in this analysis.

more accurate mapping, a probabilistic method that locates a ‘floating earthquake’ very near the facility should be used.

Conclusions

As a society we still don’t fully understand the long term implications of storing billions of tons of potentially harmful waste in large impoundments. We have been building large tailings dams for about a century, but these structures must maintain their integrity in perpetuity, so we have only a relatively short history of their performance.

What we do know is that the technology for designing and identifying the long term threats to these structures has been advancing steadily during this same time. These advances to the technology have usually been prompted by dam failures that have identified the need for further analysis, as well as the need for more conservative assumptions for design specifications and in the magnitude of natural events like floods and earthquakes that pose long term risks for these structures.

When we consider the recorded life of these structures (a century at most) to the length of time that they must function (millennia) the number of failures we have experienced in the first century of their operation is not comforting. The International Commission on Large Dams (ICOLD) summarized some of the underlying causes for these failures in 2001 Bulletin (Tailings Dams, Risk of Dangerous Occurrences, Lessons Learnt from Practical Experiences, Bulletin 121, International Commission on Large Dams, 2001):

> *"Causes (for dam failure) in many cases could be attributed to lack of attention to detail. The slow construction of tailings dams can span many staff changes, and sometimes changes of ownership. Original design heights are often exceeded and the properties of the tailings can change. Lack of water balance can lead to “overtopping”: so called because that is observed, but may be due to rising phreatic levels causing local failures that produce crest settlements." (ICOLD, 2001, p. 53)*

> *"... the technical knowledge exists to allow tailings dams to be built and operated at low risk, but that accidents occur frequently because of lapses in the consistent application of expertise over the full life of a facility and because of lack of attention to detail." (ICOLD, 2001, p. 55)*

> *"By highlighting the continuing frequency with which (dam failures) are occurring and the severe consequences of many of the cases, this Bulletin provides prima facie evidence that commensurate attention is not yet being paid by all concerned to safe tailings management." (ICOLD, 2001, p. 55)*

> *"... the mining industry operates with a continual imperative to cut costs due to the relentless reduction in real prices for minerals which has been experienced over the long term, plus the low margins and low return on capital which are the norm. The result has been a shedding of manpower to the point where companies may no longer have sufficient expertise in the range of engineering and operational skills which apply to the management of tailings." (ICOLD, 2001, p. 56)*

The Pebble case study provides interesting insight into preliminary design choices for the technical, environmental, and economic factors that drive decisions today and may affect future generations that will inherit the responsibility and liability for managing these structures. Policy guidance from an organization with responsibilities to guide the safe construction and management of large dams (ICOLD) tell us that we should be making ‘conservative’ engineering decisions when designing tailings dams. But we can also see that the recommended design specifications for the tailings dams at Pebble (and at other mines) are not based on the most conservative assumptions about the source and proximity of the largest seismic event that might be experienced at the dam site.

While these decisions may be rationalized in terms of defining 'reasonable' risk, we must also acknowledge that lessening the assumptions about the amount of risk associated with the design of the tailings dam may be motivated by lessening the present day economic cost to the builders the dam.

One well published author, in discussing mine waste disposal, has noted:

> *"… a well intentioned corporation employing apparently well-qualified consultants is not adequate insurance against serious incidents" (Morgenstern, N.R., 1998)*

By making 'reasonable' rather than 'conservative' assumptions we may be increasing the long term risk to the society which will inherit the dam and the responsibility for managing the waste, and any future costs associated with the escape of impounded waste due to an unanticipated event.

The potential for an 'unanticipated' event should drive our initial design assumptions to be more conservative, but there is ever present economic pressure to limit the extent of these conservative assumptions.

As present day events (the Gulf oil spill, which the oil industry repeatedly said couldn't happen) demonstrate that we don't fully understand the nature of industrial hazards. And, as the nuclear reactor accident that accompanied the Japan earthquake (which released 11 times as much energy as the maximum earthquake estimated by today's seismic risk experts) and tsunami have shown, we don't even know some of the critical questions we should be addressing about these hazards.

In looking at the long term risk from tailings impoundments to other resources – the economic and environmental risks to future generations, or the long term risk to a renewable fishery in Bristol Bay – policy makers should view the risks from a conservative probabilistic perspective rather than relying on assumptions about specific hazards that are likely flawed. We know that our technology and science has limits, and that there are significant economic incentives to make present day decisions about risk less, rather than more, conservative about the magnitude of these risks.[21]

A greatly expanded version of this paper titled "Long Term Risks of Tailings Dam Failure", David M Chambers and Bretwood Higman, is available at: www.csp2.org/reports

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[21] One professional in this field has described this situation thusly:

"I have concluded from all these failures that the only way is extreme conservatism, no reliance on the opinions of others—however reputable—and full site characterization and detailed analyses. For even now I am involved in the design of a tailings facility in a part of the world where the design earthquake is 8.5. That is big and could send everything down the valley and the experts say there is no problem and I think they are deluded.

I have written that I believe those who focus on single causes of failure are deluded. There is no single reason for failure of a mine geowaste facility. All failures that I have known are the result of a string of minor incidents. If but one of this string of incidents had been dealt with, no failure would have occurred. This is pretty much standard accident theory these days, although it seems not to have entered the otherwise bright minds of those who write on the failure of mine geowaste facilities. Pity them, and pity the profession for remaining so ignorant and failure oriented through failing to keep up with modern ideas and theories.

So the failure of mine geowaste facilities will keep on happening. It is inevitable. The professionals are blind and behind times. The operators are greedy and careless. Nobody reads the guidelines. The peer reviewers are old and sleepy. The pressures to profit are intense." (Slimes Dam - aka Tailings Storage Facility - Failure and what it meant to my mining mindset, April 19, 2011 by Jack Caldwell, http://ithinkmining.com)

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