LONG TERM RISKS OF TAILINGS DAM FAILURE

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Abstract

"Tailings storage facilities typically represent the most significant environmental liability associated with mining operations." (MMSD, 2002, p. 2)

Large tailings dams built to contain mining waste, among the largest dams and structures in the world, must stand in perpetuity. A catastrophic release of a large amount of tailings 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.

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. 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.[3] 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 are also fundamentally different from water supply dams in several respects.

> *"Conventional dams generally do not need to be designed to last forever, as they have a finite life. Tailings dams have a closure phase as well as an operational phase. They have to be designed and constructed to last "forever", and require some degree of surveillance and maintenance long after the mining operation has shut down, and generation of cash flow and profit has ceased." (MMSD, 2002, p. 8)*

> *"Conventional dams are viewed as an asset. As a result, their construction, operation, and maintenance receives a high standard of care and attention from owners, who often retain in-house dam engineering expertise. Contrast this to tailings dams, which have until recently been viewed by their owners as an unprofitable, money-draining part of the mining operation. The significance of this aspect is that with such attitudes a mining operation would be naturally less inclined to expend effort in the management of its tailings facility than the owner of a conventional dam." (MMSD, 2002, p. 8)*

Tailings dams differ from water supply reservoir dams in two significant ways – dam design life, and dam construction design.

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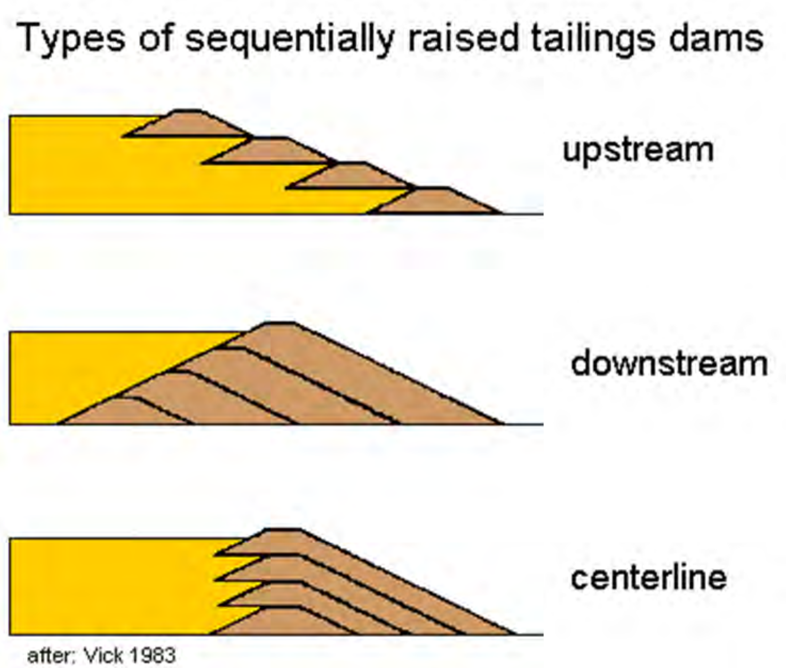
[3] See MMSD, 2002, for a short summary of the history of modern mining.

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.



Downstream construction is the safest type of construction from a seismic standpoint, but is also the most expensive option.

> *"In general, dams built by the downstream or centreline method are much safer than those built by the upstream method, particularly when subject to earthquake shaking." (ICOLD, 2001, p. 24)*

> *"Dams built by the upstream method are particularly susceptible to damage by earthquake shaking. There is a general suggestion that this method of construction should not be used in areas where there is risk of earthquake." (ICOLD, 2001, p. 47)*

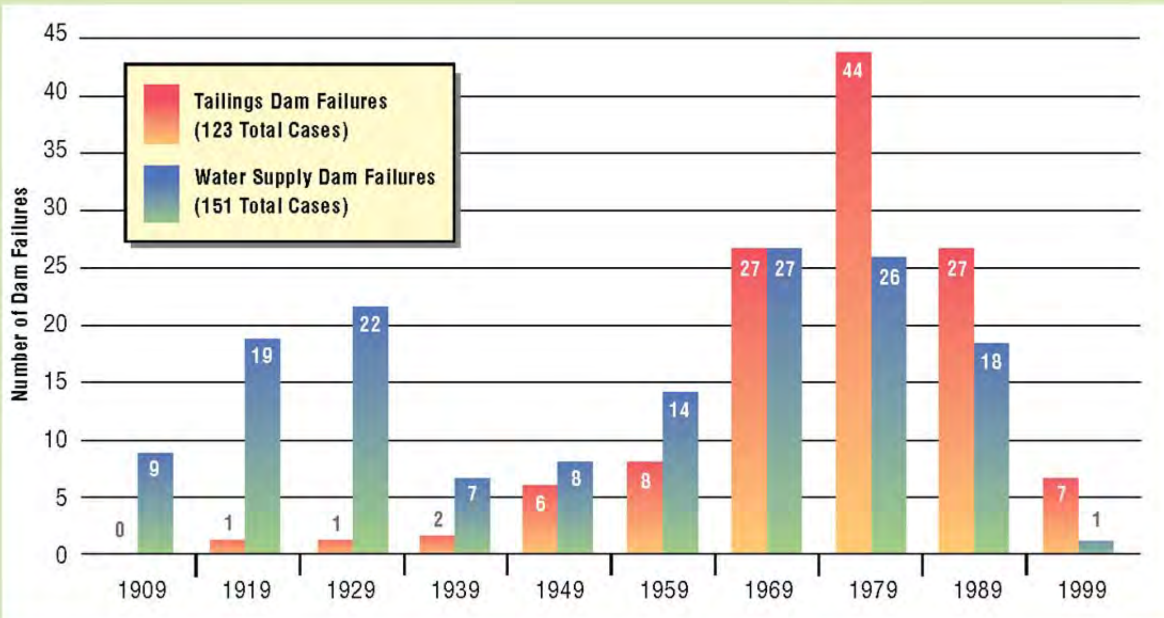
Upstream construction is the least secure because it relies on the stability of the tailings themselves as a foundation for dam construction (Davies, M.P., 2002, p. 35). Tailings are generally placed behind the dam in a slurry from the mill, and can remain saturated for long periods. Saturated, unconsolidated material is very susceptible to liquefaction under seismic loading.

But upstream dam construction, often using the coarse fraction of the tailings, is the cheapest option, and is still routinely employed in tailings dam construction today.

Centerline construction is a hybrid of downstream-type dam construction, and from a seismic stability standpoint the risk is lies between that of centerline and upstream types.

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 the figure below.



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.

Tailings Dam and Water Supply Dam Failures (UNEP, 1998)

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[4] (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). This is probably due to two factors: (1) the ability to use construction types

[4] 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.

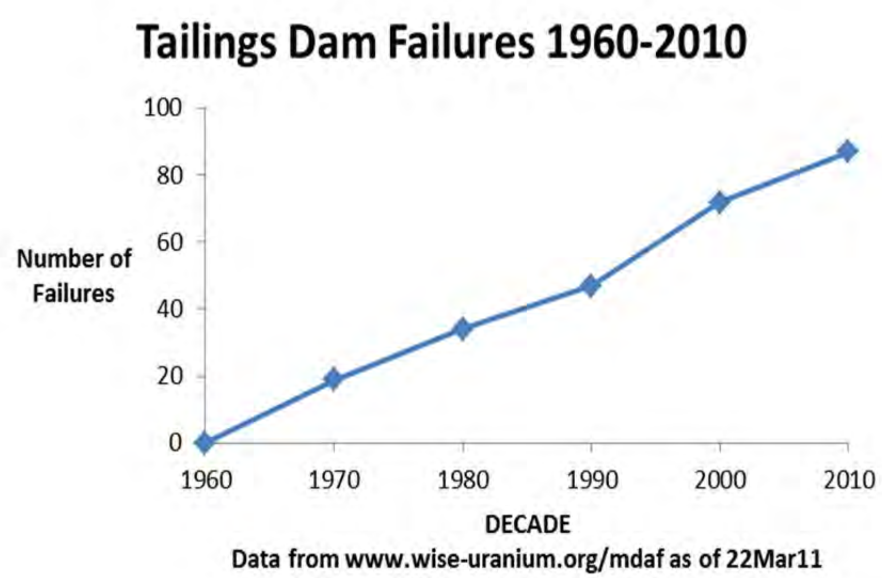
for tailings dams that are more susceptible to failure; and, (2) the fact that tailings dams are most often constructed in sequential 'lifts' over several years that make quality control more challenging relative to water supply dams that are constructed all at once.

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).[5] 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.



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).

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

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,[6] and changing weather patterns.

In ICOLD, 2001, (Figure 9) the three leading causes for tailings dam incidents[7] are 'overtopping', 'slope stability', and 'earthquakes'.[8] 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.

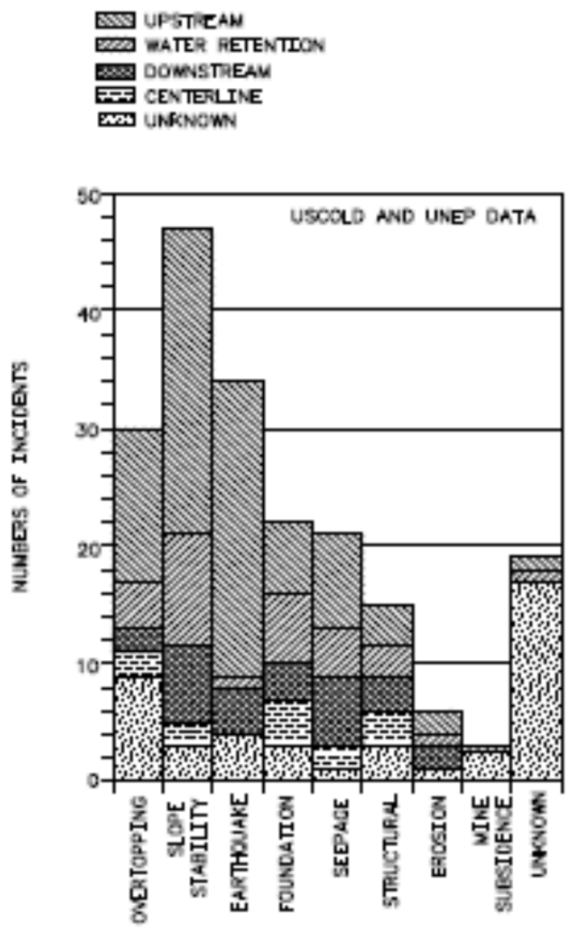


Figure 9. Tailings dam incident cause comparison with dam type.

Getting better data is a significant issue for both hydrologic event and earthquake prediction. 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.[9] 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.

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[6] 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).

[7] 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.

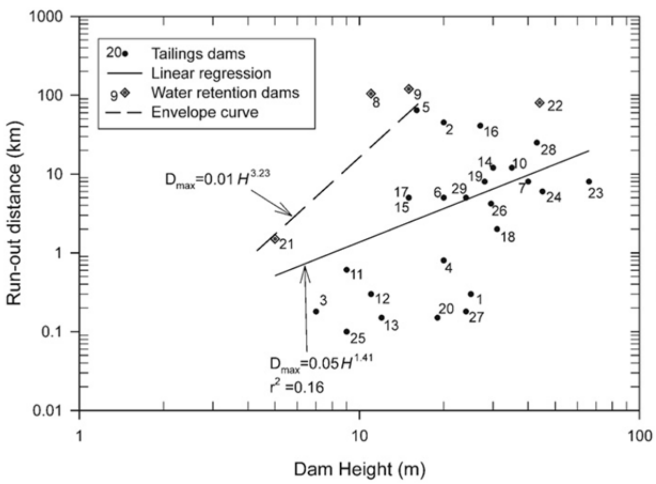
[8] "This figure (Fig.9) also indicates that the leading causes for incidents are slope instability, earthquake and overtopping: particularly so for dams constructed by the upstream method." (ICOLD, 2001, p. 20)

[9] 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)*

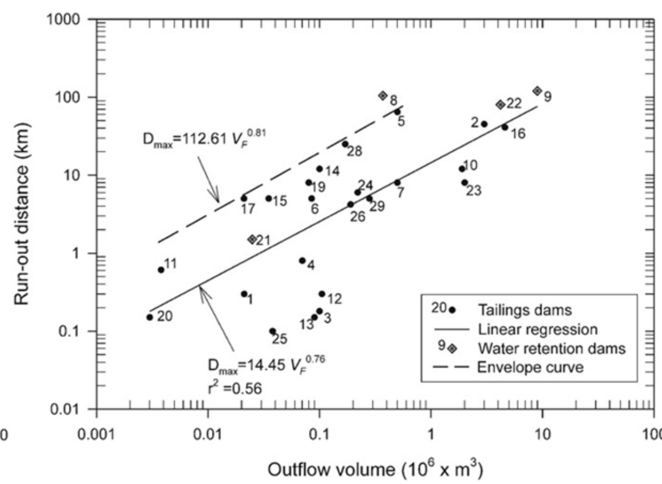
"In the early 1970's, most of the tailings dam structural technical issues (e.g. static and earthquake induced liquefaction of tailings, seepage phenomena and foundation stability) were fairly well understood and handled in designs. Probably the only significant geotechnical issue not recognised by most designers was the static load induced liquefaction (e.g. the reason for many previously "unexplained" sudden failures). However, issues related to geochemical stability were not as well recognised, and tailings impoundments were rarely designed and operated with reclamation and closure in mind." (MMSD, 2002, p. 4)

<u>When Tailings Dams Fail</u>

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.[10]



Rico, 2008b, p. 81



Rico, 2008b, p. 82

The researchers that developed these graphs 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)[11]

"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.

"Failures of tailings dams continue to occur despite the available improved technology for the design, construction and operation. The consequences of these failures have been heavy economic losses, environmental degradation and, in many cases, human loss." (ICOLD, 2001, p. 53)

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

[11] 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.

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.[12]

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.[13] 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.[14]

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

> *"Lack of control of the hydrological regime is one of the most common causes of failure. Of the cases reported here, the majority of failures were due to overtopping, slope instability, seepage and erosion; all caused by a lack of control of the water balance within the impoundments." (ICOLD, 2001, p. 31)*

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.

> *"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, 1995c, 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 may not be the Probable Maximum Flood, but a lesser event. The choice of a lesser event makes dam construction less expensive, and is often justified by evaluating the risk of potential impacts of dam failure. The risks evaluated are most often focused on the potential for loss of human life and damage to existing infrastructure. Long-term environmental impacts and cleanup costs are not emphasized, and often not considered.

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[12] 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

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

[14] 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.

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 usually 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.[15]

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 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.

Choice of the "Design Event" – How Large and How Far Away?

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.

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[15] 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

The Maximum Design Earthquake is a predicted maximum earthquake described in terms of size and distance from the dam. The MDE is typically used in computer models to evaluate how a dam will respond to earthquakes. The science used to determine the MDE, while sophisticated, has limits. The physical properties of seismic events have only been recorded since the early 1900's (Introduction to Seismology, Peter Shearer, Cambridge University Press). On most faults, no earthquake has happened within that time frame, so paleoseismology techniques must be used to estimate earthquake size in the more distant past. In many areas, the faults are not mapped or analyzed, further reducing the confidence in these determinations. There is still a great deal of uncertainty over the potential size, and more importantly the location, of future seismic events.

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.[16]

Estimating Earthquake Size and Location

Probabilistic Method: In order to estimate the earthquake potential of a given region, geologists use data from historic earthquakes, combined with studies of known faults. For well-studied faults, there are both historic measurements, and prehistoric earthquake estimates gleaned from paleosismic studies. A probability distribution over time is created based on the recurrence interval (how frequently an earthquake occurs) and the distribution of earthquake sizes on that fault. To account for the potential of earthquakes on unknown faults, this distribution is combined with information from smaller, historic earthquakes across the region. Seismic instruments can measure earthquakes down to a very small size, and record many earthquakes for which no fault is known. Statistical methods can be used to take the occurrence and size of these small earthquakes and estimate a probability distribution that includes larger earthquakes as well. In order to choose a Maximum Design Earthquake, a time frame and a probability are specified. For example, you might decide to design for the largest earthquake with at least a 2% chance of occurrence, over the next 1,000 years.

Deterministic (Fault Length) Method: Another method for determining earthquake potential is to estimate the maximum energy that could be released for a given fault. Earthquake energy in a given event is closely related to the length of rupture. Therefore, a rupture across the entire length of a fault will produce the maximum possible energy on that fault. This can be calculated if the fault length is known. The advantage of this method is that it gives a true maximum, rather than a probability, for a known fault, eliminating the uncertainties in estimating recurrence interval and earthquake size prior to instrumental measurement. The disadvantage of this method is that it does not account for unknown faults, or faults of unknown length.

If the deterministic (fault length) method is used to estimate the maximum earthquake size, location can be described simply as the closest point on the measured fault. In the probabilistic method a statistical analysis is done to determine the largest earthquake that might occur in a given geographic area.

> *"Strictly speaking, the MCE is a deterministic event, and is the largest reasonably conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. But in practice, due to the problems involved in estimating of the corresponding ground motion, the MCE is usually defined*

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[16] 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.).

statistically with a typical return period of 10,000 years for countries of low to moderate seismicity." (Wieland, M, ICOLD, 2008, p.7)

However, probabilistic methods can be viewed as inclusive of all deterministic events with a finite probability of occurrence (McGuire, c1999, p. 1).

"Deterministic and probabilistic seismic hazard analyses should be complementary. The strength of one over the other depends on the earthquake mitigation decisions to be made, on the seismic environment, and on the scope of the project. In general, more complex decisions and subtler, detailed seismic environments strongly suggest the probabilistic analysis, whereas simpler decisions and well-understood seismicity and tectonics point toward deterministic representations." (McGuire, c1999, p. 6)

The "Design Earthquake" – How Large and How Far Away?

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.[17] 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.

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.[18]

Although much progress has been made on designing large dams to withstand seismic events, there is still much progress to be made.

"Dams are not inherently safe against earthquakes. In regions of low to moderate seismicity where strong earthquakes occur very rarely, it is sometimes believed (i) that too much emphasis is put on the seismic hazard and earthquake safety of dams, and (ii) that dams designed for a seismic coefficient of 0.1 are sufficiently safe against earthquakes as none of them has failed up to now. Such arguments are not correct.

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[17] 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)

[18] 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)

For the earthquake safety evaluation the same criteria (dam must withstand the MCE ground motion) as for the hydrological safety (PMF must be released safely) have to be considered." (Wieland, M, ICOLD, 2008, p.7)

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.[19] 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.

Post Closure Monitoring and Maintenance

Even when the reclamation process has been completed for a tailings facility, there is still need for ongoing monitoring and maintenance.

"Experience regarding the long term behavior of tailings storage facilities (TSFs) is limited. Most are still in the phase of after care. Our knowledge is constantly increasing, but the closed and remediated tailings dams today (2006) are less than one or two decades old i.e. most experience of the long term stability of tailings dams after closure is still limited. In this case the long term is defined as 1000 years, or more." (ICOLD, 2006, p. 39)

The International Commission on Large Dams/United Nations Environmental Program publications describe some of the factors driving the need for long term monitoring and maintenance. These include dam stability, which requires monitoring for (ICOLD, 1996b, p. 21):

- seepage discharges through the dam, foundation, or abutments;
- phreatic surface[20] in the tailings pond and dam;
- pore pressures in the dam;
- horizontal and vertical movements in the dam

In addition to these conventional risks to dams, the need to confine tailings behind the constructed dam impose additional long-term monitoring concerns, including progressive processes that degrade dam stability over time, including (ICOLD, 2006, p. 44):

- weathering of materials
- water and wind erosion
- ice and frost forces
- intrusion by vegetation and animals

[19] 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.
[20] The phreatic surface is the surface of the water-saturated part of the ground, i.e. the groundwater level.

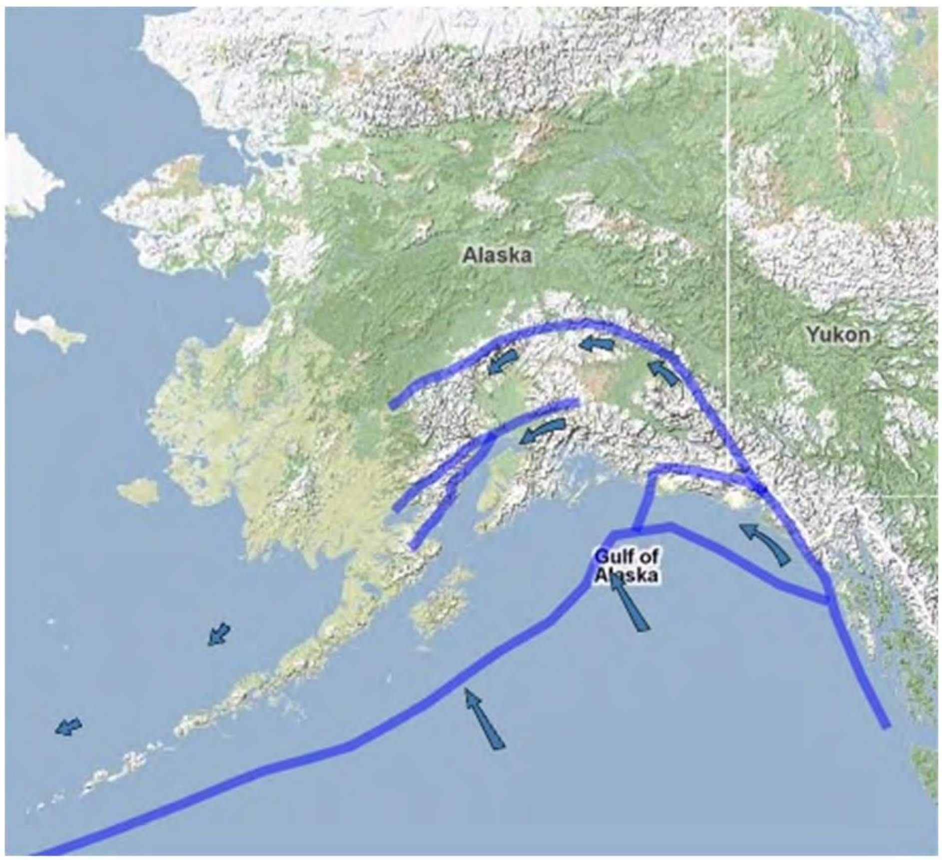
To meet these and any additional needs financial provision for not only perpetual monitoring, but also for any repairs that may be required to correct any deficiencies detected as a result of the monitoring activities, monies must be provided as a part of the financial surety for the mine.

The uncertainty in estimating the long-term monitoring and maintenance costs, and especially in providing adequate monies for repairs that may be required, is obvious.

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

The tectonic deformation of southern Alaska is driven by collision of the Pacific Plate with the North American Plate. Faults in the area around Lake Iliamna, along with most of Western Alaska, have not been studied in detail. Lake Iliamna straddles the west edge of the band of earthquakes and volcanoes that comprises the Pacific 'Ring of Fire'. It's the sort of place where active faults are likely, but little fieldwork has been done and few instruments have been deployed to measure plate motion or earthquakes.

There is good evidence that most of southcentral Alaska, called the 'Southern Alaska Block' (Haeussler, 2008) is a section of the earth's crust that is moving westward relative to the rest of North America. The Denali Fault, in the Alaska range, is the main fault that this block moves along, but there are other faults, including the Castle Mountain Fault just north of Anchorage, that allow it to deform and move westward. Additionally, there is evidence that the crust beneath the Bering Sea (called the 'Bering Block', Mackey et al., 1997), is rotating clockwise relative to North America and eastern Russia. And the Pacific Plate, which extends all the way from the Gulf of Alaska down into the South Pacific, is sliding northwards, beneath continental crust that forms Alaska.



The tectonic deformation of southern Alaska is driven by collision of the Pacific Plate with the North American Plate. This map shows some of the prominent known faults that bound different fragments of crust in southern Alaska. Arrows depict how the pieces are moving relative to North America (longer arrows mean faster motion).

At the Pebble prospect, to the east is the Southern Alaska Block, to the northwest is the Bering Block, and to the south is the Pacific Plate. It is unclear whether the Lake Iliamna region is part of the Bering Block or Southern Alaska Block. It may even be that the Bering Block and Southern Alaska Block have no distinct boundary between them (Redfield et al., 2007).

Also, there are known faults in the area that were once active, and which may or may not currently be active. The Lake Clark Fault, an extension of the Castle Mountain Fault, extends southwest from Lake Clark Pass down through Lake Clark (Haeussler et al. 2004). The Bruin Bay Fault branches from the Castle Mountain and Lake Clark faults near Tyonek, and runs south along the Cook Inlet coast into Katmai National Park.

Given the lack of instruments and geological fieldwork in the area it is very possible that subtle evidence of activity on these faults and others has simply been missed.

There are several potential sources of earthquakes that might affect Pebble. The source for the largest potential earthquake comes from the subduction zone along the Aleutian Trench south of the coast in the Gulf of Alaska. This was the source of the famous 1964 magnitude 9.2 Alaska earthquake.

There are also a series of fault systems that parallel the Aleutian Trench on the Alaska mainland north of the subduction zone. One of these faults is the Denali Fault zone. A magnitude 7.9 earthquake occurred along the Denali Fault in 2002. Another of these parallel faults is the Lake Clark Fault. This is the fault that comes closest to Pebble.

A final seismic threat is what is generally termed as a "floating' earthquake, that is, one that is not associated with a known fault. It is generally assumed that this floating earthquake would occur very near to the site being evaluated, but could also be of a lesser magnitude than an earthquake associated with a known fault system. Any actual earthquake will occur on a fault, but the "floating" earthquake is a statistical construct used to estimate the risk of an earthquake on an unknown fault.

The energy from an earthquake dissipates as it radiates from the source (the source is a planar surface extending into the earth rather than a point). So, the further away a location is from the source of the earthquake, the less energy is available to cause motion at the dam location. The 1964 earthquake ruptured to within approximately 125 miles from the Pebble site, while the 2002 rupture extended to within about 260 miles. The Lake Clark Fault (an extension of the Castle Mountain Fault) is less than 20 miles from Pebble. Therefore, the Lake Clark Fault is much more likely to be the source of the Maximum Credible Earthquake at the Pebble Mine site.

This is especially problematic, because the location of the Lake Clark Fault is not known, and it is possible that it runs directly through the area of proposed development at Pebble (Haeussler et. al., 2004). The Lake Clark Fault is almost certainly less active than the Denali Fault, meaning that it has a longer recurrence interval between earthquakes. However, in the long time span that a tailings dam is required to maintain integrity, it has a significant chance of producing an earthquake of 7.9 or similar magnitude. A difference of only a mile in the location of this fault could have a dramatic impact on the potential ground acceleration at the tailings dam, and hence on the engineering constraints for the dam. The larger the earthquake, the more energy, and the longer the period of shaking that will take place at the dam site.

Alaska Regulatory Requirements

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, in Appendix B of this paper)

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, in Appendix B of this paper).[21] Class II dams must withstand seismic 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, T able 6-2). Note that it is not mandatory to use the Maximum Credible Earthquake as the Maximum Design Earthquake for a Class I dam.

Choice of MCE & MDE at Pebble

As discussed in Knight-Piesold, 2006, under Alaska dam classification regulations a tailings dam would be classified as a Class II dam (Knight Piesold Ltd., 2006, Section 3.2.3 Design Earthquakes).

The most recent information about seismic considerations for tailings dams (Tailings Storage Facility - TSF,) at the Pebble site comes from the Preliminary Assessment of the Pebble Project, Southwest Alaska, Wardrop-Northern Dynasty Mines, February 17, 2011, p. 52:

> *"Recognizing the seismic characteristics of Alaska, particular attention has been paid to understanding seismic risk factors in the TSF design. The embankment design parameters conform to Alaska Dam Safety regulations, under which they would be classified as Class II structures. Extensive research has been conducted into historical seismic events, in Alaska generally and in southwest Alaska in particular, to support an assessment of the probability and magnitude of seismic events that might affect Pebble.*
>
> *Analysis of public domain literature was undertaken to determine the location of likely sources for seismic events near Pebble, with the most likely candidate identified as the Lake Clark Fault. The location of this fault has been identified as part of a geophysical survey of the region. Using these data, as well as public domain information, the energy that might be released if a major earthquake were to occur along the Lake Clark Fault has been determined.*
>
> *The parameters used in this analysis are extremely conservative. For instance, while there is no evidence of movement along the Lake Clark Fault since the last glaciers receded some 10,000 years ago, TSF seismic design criteria assume that it is an active fault. Further, sections of the Lake Clark Fault nearest the Pebble Project are actually splays of the main fault and thus unlikely to release the same energy as if the entire fault was to move. Nonetheless, TSF seismic design criteria have conservatively assumed that the Lake Clark Fault is both active and capable of a seismic event equivalent to slippage along the entire fault."*

This 2011 summary appears to reflect earlier work done by Knight-Piesold Ltd., for Northern Dynasty in 2006. In the sections on seismic risk from the Knight-Piesold Ltd., 2006, Report.[22]

> *"Consistent with current design philosophy for geotechnical structures such as dams, two levels of design earthquake have been considered: the Operating Basis Earthquake (OBE) for normal operations; and the Maximum Design Earthquake (MDE) for extreme conditions (ICOLD, 1995a).*

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[21] 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, 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.

[22] See Appendix A of this paper for these sections in their entirety.

Values of maximum ground acceleration and design earthquake magnitude have been determined for both the OBE and MDE.

Appropriate OBE and MDE events for the facilities are determined based on a hazard classification of the facility, with consideration of the consequences of failure. The hazard classification was carried out using the criteria provided by the document "Guidelines for Cooperation with the Alaska Dam Safety Program" (2005). Classification of the facilities is carried out by considering the potential consequences of failure, including loss of life, economic loss and environmental damage. The hazard classification has been assessed as at least Class II (Significant). The OBE and MDE are selected based on the dam hazard classification and an appropriate earthquake return period, as defined by the "Guidelines for Cooperation with the Alaska Dam Safety Program" (2005).

For a Class II hazard classification, the OBE is selected from a range of return periods from 70 to 200 years, depending on the operating life of the facility, the frequency of regional earthquakes and the difficulty of quickly assessing the site for repairs. The impoundment would be expected to remain functional during and after the OBE and any resulting damage should be easily repairable in a limited period of time.

The MDE is typically selected from a range of return periods from 1,000 to 2,500 years for a Class II hazard classification. However, the MDE for the Pebble TSF has been conservatively based on a Class I hazard classification making it equivalent to the Maximum Credible Earthquake (MCE), which has a bedrock acceleration of 0.30 g corresponding to a magnitude M7.8 earthquake, occurring along the nearby Castle Mountain Fault system." (Knight Piesold Ltd. 2006, Section 2.5 Seismicity and Embankment Stability)

Although the Pebble NDM consultants have decided to base their calculations on the "Maximum Credible Earthquake", their use of the deterministic method for the MDE/MCE does not appear to meet ICOLD standards for locating the MDE/MCE. The Pebble NDM consultants assume the Lake Clark Fault is 18 miles from the minesite, and using this deterministic location ignores 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.[23]

Although Knight-Piesold considers that Maximum Design Earthquake for the Pebble dam design to be the Maximum Credible Earthquake, an examination of Table 3.1 of the report reveals that the 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, in Appendix A of this paper). The choice for the magnitude of the Maximum Credible Earthquake for Pebble is not the same, and 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, in Appendix A of this paper) is as large as that of the horizontal acceleration for a 1 in 10,000 year event would be.

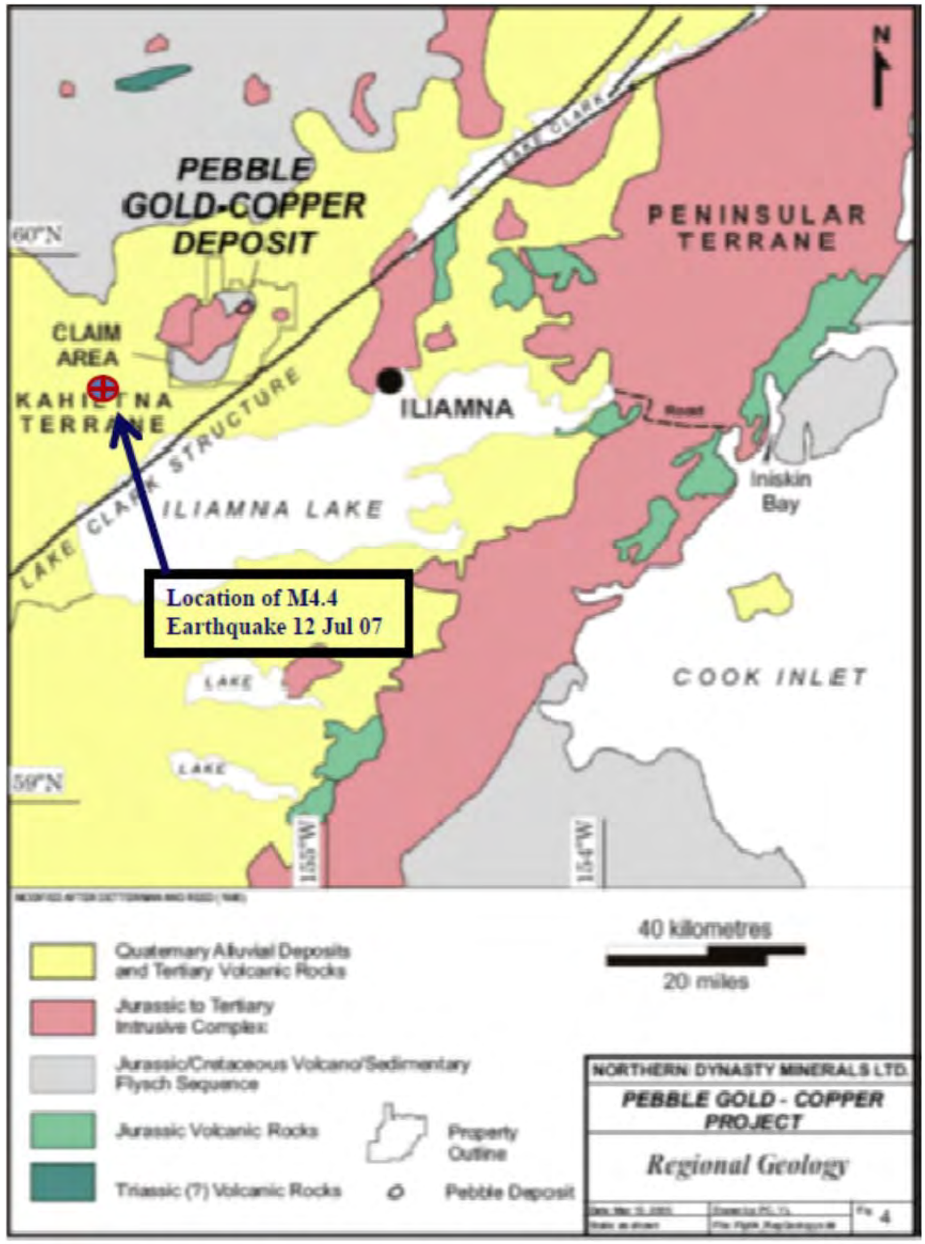
Using a seismic event with a return period of 5000 years implies that the dam will experience an earthquake of this magnitude sometime during the 5000 year period. Over 10,000 years the dam could experience an earthquake of this size twice. Using an earthquake with a return period of 10,000 years would probably mean that the dam would have to be designed to withstand more energy and longer

[23] Table 3.2, Section 3.2.2 Seismic Hazard Analyses, Knight Piesold Ltd., 2006, in Appendix A of this paper, 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.

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 size of the Maximum Design Earthquake is the location of the Maximum Credible Earthquake. Knight-Piesold has not chosen to locate its Maximum Credible Earthquake as a floating earthquake near the dam site, but picked a location for the Maximum Credible Earthquake deterministically18 miles away (Knight Piesold Ltd., 2006, Section 3.2.2 Seismic Hazard Analyses, Table 3.2, in Appendix A of this paper). As mentioned, 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 Knight-Piesold. Knight-Piesold has 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 Appendix A of this paper).



This earthquake had a magnitude of 4.4 and a depth of 6.2 km. (Alaska Earthquake Information Center)

In fact, there was a small earthquake on July 12, 2007, located approximately 20 miles from the Pebble location. 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, www.aeic.alaska.edu). 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 Design 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 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 likelihood of extreme events is proportionally large in the long-term phase." (ICOLD, 1996a, p. 35)*

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.[24]

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[24] 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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APPENDIX A

KNIGHT PIESOLD PEBBLE PROJECT SEISMICITY REPORT EXCERPTS

Northern Dynasty Mines Inc. Pebble Project, Tailings Impoundment A Initial Application Report (Ref. No. VA101-176/16-13), Knight Piesold Ltd., September 5, 2006

3.2 SEISMICITY

3.2.1 Regional Seismicity

Alaska is the most seismically active state in the United States and in 1964 experienced the second largest earthquake ever recorded worldwide. Both crustal earthquakes in the continental North American Plate and subduction earthquakes affect the Alaska region. Historically, the level of seismic activity is highest along the south coast, where earthquakes are generated by the Pacific Plate subducting under the North American plate. This seismic source region, known as the Alaska-Aleutian megathrust, has been responsible for several of the largest earthquakes recorded, including the 1964 Prince William Sound magnitude 9.2 (M9.2) earthquake. There is potential for a future large subduction earthquake (M9.2+) along the southern coast of Alaska, and this seismic source zone is located approximately 125 miles from the project site.

Several major active faults in Alaska have generated large crustal earthquakes within the last century. A magnitude 7.9 earthquake occurred along part of the Denali fault in 2002, approximately 44 miles south of Fairbanks. The western portion of the Denali Fault trends in a northeast-southwest direction, approximately 125 miles north of the project site. Approximately 19 miles northeast of the project site is the western end of the northeast-southwest trending Castle Mountain Fault, which terminates approximately at the northwest end of Lake Clark. A magnitude 7.0 earthquake associated with this fault occurred in 1933. The Denali and Castle Mountain faults are capable of generating large earthquakes with magnitudes in the range of M7.5 to M8.0.

3.2.2 Seismic Hazard Analyses

The seismic hazard for the Pebble project has been examined using both probabilistic and deterministic methods of analysis.

Maximum bedrock accelerations have been determined based on the published USGS probabilistic seismic hazard model for Alaska. This was developed by the USGS to produce their latest seismic hazard maps for Alaska. Maximum horizontal acceleration values have been determined for return periods ranging from 100 years to 5000 years. The results have been summarized in Table 3.1, in terms of earthquake return period, probability of exceedance and maximum acceleration. The calculated probabilities of exceedance assume a design operating life of 20 years. For a return period of 475 years the corresponding maximum acceleration is 0.14g, implying a moderate seismic hazard.

TABLE 3.1

NORTHERN DYNASTY MINES INC.
PEBBLE PROJECT
Tailings Impoundment A - Initial Application Report
PRELIMINARY SUMMARY OF PROBABILISTIC SEISMIC RISK

M:\1\01\00176\16\A\Report\Report 13_dam application - Site A\Rev 0\Tables\[Table 3.1 and 3.2 - Design Scope.xls]Table 3.1

Print: Sep 8, 06
Rev: Aug 16, 06

Return Period (Years)	Probability of Exceedance[1] (%)	Maximum Acceleration[2] A (g)
108	16.9	0.08
224	8.5	0.10
475	4.1	0.14
975	2.0	0.18
2475	0.8	0.24
4975	0.4	0.30

Notes:
1) Probability of Exceedance calculated for a design life of 20 years.

$$q = 1 - \exp(-L/T)$$

where, q = probability of exceedance
L = design life in years
T = return period in years

2) Maximum Accelerations are for values on bedrock/firm ground.

A deterministic analysis has been carried out by considering known seismic sources and fault systems in the region and applying a maximum earthquake magnitude to each potential source. The resulting deterministic acceleration at the study site for each source is considered to be the maximum credible acceleration that can occur, on the basis of available geologic and tectonic information. The maximum accelerations were calculated using the mean plus one standard deviation values with appropriate ground motion attenuation relationships. The ground motion attenuation relationships used are applicable to western North American earthquakes, and are consistent with those used by the USGS. As indicated by the review of regional seismicity summarized above, the three most prominent seismic sources in the region of southwestern Alaska are the Denali Fault, Castle Mountain Fault and the Alaska-Aleutian megathrust. The results of the deterministic analysis are presented in Table 3.2, including the potential maximum magnitude for each of these seismic sources, the estimated minimum epicentral distance and the calculated maximum acceleration at the project site. Based on these results a Maximum Credible Earthquake (MCE) of M7.8 causing a maximum bedrock acceleration of 0.3g has been selected for the Pebble project site.

TABLE 3.2

NORTHERN DYNASTY MINES INC.
PEBBLE PROJECT
Tailings Impoundment G - Initial Application Report
PRELIMINARY SUMMARY OF DETERMINISTIC SEISMIC HAZARD ANALYSIS

Print: Sep 8, 06
M:\1\01\00176\16\A\Report\Report 12_dam application - Site G\Rev 0\Tables\[Table 3.1 and 3.2 - Design Scope.xls]Table 3.2 Rev: Aug 16, 06

A Earthquake Source	Maximum Magnitude (Mw)	Epicentral Distance (miles)	Maximum Acceleration[1] (g)
Castle Moutain Fault	7.8	18	0.30
Denali Fault - Central	8.0	125	0.08
Mega-Thrust Subduction Event	9.2	125	0.17

Notes:
1) Maximum Accelerations are for values on bedrock/firm ground.

3.2.3 Design Earthquakes

Consistent with current design philosophy for geotechnical structures such as dams, two levels of design earthquake have been considered: the Operating Basis Earthquake (OBE) for normal operations; and the Maximum Design Earthquake (MDE) for extreme conditions (ICOLD, 1995a).

Appropriate OBE and MDE events for the facilities are determined based on a hazard classification of the facility, with consideration of the consequences of failure. The hazard classification was carried out using the criteria provided by the document "Guidelines for Cooperation with the Alaska Dam Safety Program" (2005). Classification of the facilities is carried out by considering the potential consequences of failure, including loss of life, economic loss and environmental damage. The hazard classification has been assessed as at least Class II (Significant). The OBE and MDE are selected based on the dam hazard classification and an appropriate earthquake return period, as defined by the "Guidelines for Cooperation with the Alaska Dam Safety Program" (2005).

For a Class II hazard classification, the OBE is selected from a range of return periods from 70 to 200 years, depending on the operating life of the facility, the frequency of regional earthquakes and the difficulty of quickly assessing the site for repairs. The impoundment would be expected to remain functional during and after the OBE and any resulting damage should be easily repairable in a limited period of time.

The MDE is typically selected from a range of return periods from 1,000 to 2,500 years for a Class II hazard classification. However, the MDE for the Pebble tailings storage facilities embankments have been conservatively based on a Class I hazard classification making it equivalent to the MCE, which has a bedrock acceleration of 0.30 g corresponding to a magnitude M7.8 earthquake, occurring along the nearby Castle Mountain Fault system. [25] The MCE is considered to be the seismic event with the highest possible maximum ground acceleration at the project site. A M9.2+ megathrust earthquake does not impose the highest maximum ground acceleration at the Pebble site (predicted maximum acceleration of 0.17 g), but the event is also considered in seismic design analyses due to the very long duration of ground shaking associated with earthquakes of this magnitude.

The tailings storage facility embankments will be designed to meet or exceed the Alaska Dam Safety requirements to ensure the embankment will remain stable without release of tailings or process water for all loading cases, including the MDE and the M9.2+ megathrust event.

5.2 DESIGN OBJECTIVES

The principal objectives of the design and operation of the tailings storage facility are to provide secure containment for tailings solids, potentially reactive waste rock and impounded process water. The design and operation of the tailings storage impoundment is integrated with the overall water management objectives for the entire mine development in that surface runoff from disturbed areas within the mine site is controlled, collected, and contained. An additional requirement is to allow effective reclamation of the tailings impoundment and associated disturbed areas at closure to meet end use land objectives.

Preliminary studies have been conducted to develop feasible options that satisfy these fundamental objectives at this stage of design, but additional investigation and design work will be necessary as contemplated in the Alaska Dam Safety Program. The preliminary Design Basis for the impoundment is included in Table 5.1.

TABLE 5.1

NORTHERN DYNASTY MINES INC.
PEBBLE PROJECT
Tailings Impoundment A – Initial Application Report
PRELIMINARY DESIGN BASIS

M:\1\01\00176\16\A\Report\Report 13_dam application - Site A\Rev 0\Tables\Table 5.1 - Design   Rev'd: August 16, 2006

ITEM	DESIGN CRITERIA

	<u>KP Design Basis</u>
	• Operating Basis Earthquake (OBE) ≥ 1/200 year
	  o Magnitude = M7.5
	• Maximum Design Earthquake (MDE) = 1/2500 year
	  o Magnitude = M7.8
	  o MDE corresponds to the Maximum Credible Earthquake (MCE)
	    ▪ Maximum firm ground acceleration = 0.3g

Stability Analyses	

Stability Analyses	• Upstream and downstream stability analyses will be completed using the limit equilibrium computer modeling program SLOPE/W.
	• The embankments will be designed to meet of exceed the minimum acceptable factors of safety (based on the U.S. Army Corps of Engineers) for the following cases:
	  o End of embankment construction
	  o Long term (full tailings pond)
	  o Seismic (pseudo-static)
	  o Post-Liquefaction

[25] *Author's note: This statement does not agree with the information provided in Table 5.1, but does agree with Table 3.1*

APPENDIX B

ALASKA DAM CLASSIFICATION SEISMIC STABILITY REGULATIONS

Guidelines for Cooperation with the Alaska Dam Safety Program, Prepared by Dam Safety and Construction Unit, Water Resources Section, Division of Mining, Land and Water, Alaska Department of Natural Resources, June 30, 2005, Sections 6.2, 6.3, 6.4

2.4 Hazard Potential Classification

The hazard potential classification is the main parameter for determining the level of attention that a dam requires throughout the life of the project, from conception to removal. The hazard potential classification represents the basis for the scope of the design and construction effort, and dictates the requirements for certain inspections and emergency planning. The ADSP uses three classifications for dams based on the potential impacts of failure or improper operation of a dam:

- Class I (high)
- Class II (significant)
- Class III (low)

The hazard potential classifications are explained in detail in 11 AAC 93.157 and are summarized in Table 2-1.

Dams are classified based on theoretical estimates of the potential impact to human life and property if the dam were to fail in a manner that is typical for the type of dam under review, or if improper operation of the dam could result in adverse impacts. The actual or perceived quality of design and construction and the condition of the dam are irrelevant for the classification, but may influence other requirements such as the frequency of monitoring, the scope of PSIs, and the content of O&M manuals and EAPs.

To determine the hazard potential classification consistently and equitably for projects, Dam Safety developed the Hazard Potential Classification and Jurisdictional Review Form in Appendix A, as previously mentioned. This form should be completed by a qualified engineer based on the existing or proposed configuration of the dam, and submitted to Dam Safety for review and concurrence.

Table 2-1. Hazard Potential Classification Summary

Hazard Class	Effect on Human Life	Effect on Property
I (High)	Probable loss of one or more lives	Irrelevant for classification, but may include the same losses indicated in Class II or III
II (Significant)	No loss of life expected, although a significant danger to public health may exist	Probable loss of or significant damage to homes, occupied structures, commercial or high-value property, major highways, primary roads, railroads, or public utilities, or other significant property losses or damage not limited to the owner of the barrier Probable loss of or significant damage to waters identified under 11 AAC 195.010(a) as important for spawning, rearing, or migration of anadromous fish
III (Low)	Insignificant danger to public health	Limited impact to rural or undeveloped land, rural or secondary roads, and structures Loss or damage of property limited to the owner of the barrier

The form presented in Appendix A is designed as a "tickler" to remind the engineer of important aspects that should be considered in the review. In addition, the form is designed to be progressive. Three levels of review are available:

Preliminary – An initial, conservative assignment based on a visual inspection of the dam, the reservoir, the downstream reach, and other limited, readily available information such as aerial photography and topographic maps

Qualitative – A limited engineering evaluation that may involve crude hydrological estimates, simplistic peak discharge calculations for a dam failure or mis-operation, open-channel flow calculations, elevation or cross-section surveys, and simplistic data used with conservative assumptions
that includes failure mode evaluation, computerized dam-break and hydraulic-routing models, detailed hydrological estimates, and good-quality input data

Potential Future Development and Hazard Potential Classification

A hazard potential classification determines the standard for the design, construction, and operation of the dam during the life of the project. If additional downstream development is likely, the dam should be designed and constructed to standards for the higher classification, although the dam may be classified and managed for existing conditions until the future development occurs.

The higher levels of analyses and detail carry more credibility in the assignment of the classification. For example, a preliminary assignment of a Class II (significant) hazard potential could be overruled if a qualitative or quantitative review demonstrates that the potential for adverse impacts is actually low. In another example, if new development occurs below an existing Class III (low) hazard dam, a qualitative analysis may be used to upgrade the dam to a Class I (high) hazard, whereas a quantitative analysis may demonstrate that a Class II (significant) hazard is the appropriate classification. Additional information about dam failure analysis is presented in Section 9.3.

The ADSP hazard potential classifications were modified in the current regulations to be consistent with guidance contained in the following source:

Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams, published by the Federal Emergency Management Agency (1998b)

Admittedly, much of the terminology used in 11 AAC 93.157 is not specific; for example, "probable" is not currently defined. Dam Safety will consider arguments presented by dam owners for hazard potential classifications that are in dispute, including risk assessments that quantitatively assign probabilities to certain outcomes. Nevertheless, those arguments should be cooperatively developed, technically sound, and justifiable. Additional information about risk assessments is presented in Section 12.3. The following references may also be helpful in assigning the hazard potential classification:

Evaluation Procedures for Hydrologic Safety of Dams, published by the American Society of Civil Engineers (1988)

"Dam Break Inundation Analysis and Downstream Hazard Classification," Technical Note 1, in *Dam Safety Guidelines,* published by the Washington State Department of Ecology (WSDOE) (1992)

……………..

6.2 Stability

Stability must be demonstrated for all types and hazard potential classification dams under a variety of loading conditions. Many acceptable empirical and numerical methods are available for evaluation of the stability of dams. The scope of the stability analysis should be defined in the design scope memorandum, including methods of analysis and verification and references for proposed safety factors, or objectives of deformation analyses or finite element analyses.

The general guidance shown in Table 6-1 should be considered when defining the scope of the stability analysis in the design scope proposal. (See Section 5.1.7.)

The stability analysis requirements for hazard potential classification dams are summarized below.

Class I (high) hazard potential dams – Detailed stability analysis is required. All computer stability analyses must be verified with manual calculations or other approved methods.

Class II (significant) hazard potential dams – Detailed stability analysis is required. Graphical or empirical evaluations may be used to verify computer results.

Class III (low) hazard potential dams – Published empirical or graphical methods may be adequate for small embankment dams less than 25 feet in height. Embankment dams greater than 25 feet in height should be evaluated in the same manner as Class II dams. Other types of dams, such as concrete, steel, or timber frame dams, may require a combination of methods.

For any given analysis, all input data and results must be clearly documented, including assumptions, sources of information, references, and computer outputs.

Table 6-1. General Guidance for a Stability Analysis

Hazard Potential	Dam Type	Computer Analysis	Graphical or Empirical Analysis	Manual Analysis	Finite Element Analysis
Class I	All	P		V	S
Class II	All	P	V		S
Class III	Earth and rock fill, <25 feet tall	O, S	P	O	
Class III	Earth and rock fill, 25 feet or taller	P	V		
Class III	All others	S	O	O	S

P = Primary method of analysis

S = May be required under special circumstances

V = Verification of primary method

O = Optional method of analysis

6.3 Seismicity

Evaluation and design of all new dams, or major modifications of existing dams should consider the effects of seismicity on the stability and performance of the facility, including appurtenant structures, reservoir, and associated equipment. A study to assess the seismicity is required for all dams. Depending on the complexity of the project, this study may require an interdisciplinary team that includes seismic, geologic, geotechnical, and structural engineering specialists.

6.3.1 Minimum Scope

The scope and detail of each seismic study will depend on the dam hazard potential classification and location, the regional seismic environment, and the site-specific geologic and topographic conditions. However, each study should address the following four key elements:

Define the seismic environment such as regional earthquake sources, historical activity, and recurrence rates, and characterize the levels of potential ground motions such as duration, frequency, amplitude and predominant period of ground vibrations, and peak ground accelerations, as needed for design and monitoring during operation

Evaluate the potential for fault movements rupturing the surface at or near the dam, liquefaction, lateral ground spreading and cracking, and overtopping caused by seiches or waves induced by slope failures around the reservoir

Analyze the dynamic response of the dam to inertial forces and potential reductions or loss of strength and stiffness in the foundation and dam materials as a function of the design ground motions

Analyze the facility to verify that each element, including embankments, foundations, appurtenances, and reservoir, will adequately resist translational (sliding wedge or block), rotational or flow-type slides, or excessive settlements and deformations during the design earthquakes

6.3.2 Design Earthquake Levels

Two levels of design earthquake must be established:

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 lifetime of the project. All critical elements of the project (such as dam, appurtenant structures, reservoir rim, and equipment) should be designed to remain functional during the OBE, and any resulting damage should be easily repairable in a limited time. The OBE can be defined based on probabilistic evaluations, with the level of risk (probability that the magnitude of ground motion will be exceeded during a particular length of time) being determined relative to the hazard potential classification and location of the dam.

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. All critical elements of the dam and appurtenant structures for which the collapse or failure could result or precipitate an uncontrolled

Maximum Credible Earthquake

The terminology used for describing various design earthquakes and seismic hazards is inconsistent in the various references. The maximum credible earthquake (MCE) is defined herein as the greatest earthquake that reasonably could be generated by a specific seismic source, based on seismological and geologic evidence and interpretations. The MDE and OBE are defined in the text. Other terminology may be acceptable, but specific references and definitions must be included.

release of the reservoir must be designed to resist the MDE. In addition, the dam and appurtenances must be designed to resist the effects of the MDE on the reservoir and reservoir rim. The MDE may be defined based on either deterministic or probabilistic evaluations, or both.

Table 6-2 provides a range of probabilistic return periods (risk) considered appropriate for defining the OBE and MDE, as a function of the hazard potential classification of the dam. Within the context of these ranges, the OBE return period for a given project should be selected in direct correlation with the frequency of regional earthquakes, the useful life span of the facility, and the difficultly of quickly accessing the site for repairs. The return period selected for the MDE should be selected in direct correlation with the magnitude of the maximum credible earthquake (MCE) for the known or suspected regional sources; the dam type, size, and geometry; and the reservoir capacity. Further guidelines for selecting the ground motions associated with these two levels of seismic hazard are provided in Dobry et al. (1999) and USCOLD (1999).

Table 6-2. Operating- and Safety-Level Seismic Hazard Risk

Dam Hazard Classification	Return Period, Years	
	Operating Basis Earthquake	Maximum Design Earthquake
I	150 to >250	2,500 to MCE
II	70 to 200	1,000 to 2,500
III	50 to 150	500 to 1,000

6.3.3 Seismic Study Phases

Seismic studies for new dam design should be conducted in two phases, which are described below.

Seismic report phase – This phase should occur early in the planning of the project and be included with the Preliminary Design Package submittals described in Subsection 5.2.5. The seismic report will include preliminary evaluations as needed to establish an understanding of the potential influence of the OBE and MDE on the type, geometry, and size of the dam and reservoir. Given the preliminary nature of this phase, evaluations can generally be based on published information and simplified methods. After the risks have been established, preliminary values for the OBE and MDE parameters can be estimated based on regional geologic mapping (for example, USGS publications and Plafker and Berg, 1994) and seismological studies (for example, Wesson et al., 1999; and USGS National Seismic Hazard Mapping Project – Interactive Deaggregation, 2003). Evaluations of the potential for liquefaction should be presented based on the local geology, historical record, and simplified methods with the use of standard penetration test values from the geotechnical evaluation (for example, Seed et al., 2001; and Youd and Idriss, 1997). Evaluations of the response and stability of the dam should be presented by using limit-equilibrium or linear-elastic analysis and generic response spectra found in applicable design codes or standards (see methods in Kramer, 1996).

The seismic report phase should also refine the scope and detail of the evaluations to be performed during the subsequent design evaluations of the facility conducted in the second phase of the seismic evaluation of the dam. If the associated risks are high because of the location of the dam and its hazard potential classification, more sophisticated analyses may be required (USCOLD, 1999); for example, with deterministic and probabilistic evaluations or acceleration time histories.

Seismic design phase – This phase should occur during the detailed design of the project and be included in the engineering design report submitted as part of the Detailed Design Package and described in Subsection 5.3.1. The seismic design phase of the seismic study will include formal evaluations of each critical element of the dam as needed to assure that the facility meets the performance requirements under the OBE and MDE. The effort and sophistication of the work conducted during this phase of the seismic study will depend on the hazard potential classification of the dam, and the magnitude of the OBE and MDE. For example, the dynamic and stability evaluations for all Class I and II dams located in a highly seismic region (with peak ground accelerations greater than about 30% to 40% of gravity or peak shear strains greater than about t2%) should utilize advanced one- and two-dimensional site response analysis techniques (for example, Lee & Finn, 1978; and Idriss et al., 1973) to more accurately model the nonlinear behavior of soil subject to earthquake loading. On the other hand, the dynamic stability evaluations for Class III dams or Class II dams located in regions with low seismicity (with peak ground accelerations less than about 5% to 10% of gravity) can utilize the same simplified methods followed in the seismic report phase, and no additional detailed evaluation may be required. However, the simplified methods presented in the seismic report should be reviewed with respect to the final design of the dam, and should be revised if necessary. Evaluations of Class I and II dams located in regions of moderate seismicity can utilize techniques between these ranges, such as equivalent-linear, one-dimensional, site response analysis (for example, Idriss and Sun, 1992).

6.4 Seepage

Seepage must be considered for all hazard potential classification dams; however, the scope of the analysis depends on a number of factors, including the size and type of dam and the foundation and construction materials. The following are conditions and suggested levels of evaluation based on the hazard potential classification of the dam.

All hazard potential class dams

The material properties, including permeability, must be estimated for both the foundation and construction materials.

Filters must be included in all embankment dams between core materials and drains.
Soil filter criteria must be demonstrated based on actual gradation tests. References to filter criteria standards must be included.

Appropriate seepage cutoff or reduction measures must be included to limit gradients and prevent piping and erosion.

All dams must include the appropriate drainage features to control seepage pressures and gradients, including uplift.

Phreatic surfaces must not daylight on the downstream face of embankment dams.

Appropriate measures to control seepage along penetrations through the dam or at contact planes between different materials, such as the interface between concrete and soil fill, must be included.

Class III (low) hazard potential dams

Empirical evaluations combined with engineering controls may be used to address seepage.

Published values for material properties may be used in lieu of laboratory testing to a limited extent; however, sufficient index testing must be completed to accurately classify all materials to be used in construction.

Class II (significant) hazard potential dams

Foundation conditions must be thoroughly evaluated in the geotechnical program, including rock coring and packer testing, as appropriate.

Laboratory testing must be used to determine permeability and index properties of the core, filter, and drainage materials. Published permeability values may be used for coarse- grained drainage materials. In situ soil and rock, excavated material to be reused, and borrow sources must be tested.

Appropriate foundation preparations, such as cleaning, slush grouting, pressure grouting, and dental concrete, must be included in the construction specifications.

A numerical analysis may be required for certain Class II dams for which seepage control is a primary performance parameter.

Class I (high) hazard potential dams

All Class II conditions apply.

Geotextile filters may not be used as primary filters in critical components of Class I dams.

A numerical analysis must be completed.

Seepage Monitoring

All dams should be monitored for seepage. Increases in seepage rates or turbidity can be key indicators of a developing failure situation. Seepage monitoring requirements should be specified by the engineer and included in the operations and maintenance manual discussed

in Chapter 8. Seepage monitoring software is available from the Federal Emergency Management Agency's National Safety Program. Contact Gene