The Use of the Silva-Lambe-Marr Method for Estimating the Annual Probability of Failure of the Tailings Dams at the Copper Mountain Mine, British Columbia, Canada

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LIGHTNING SUMMARY

The Copper Mountain Tailings Management Facility in British Columbia, Canada, stores 309 million metric tons of mine tailings behind two dams constructed out of cycloned, uncompacted sand with heights of 164.5 and 172.5 meters. The dam failure consequence category is Extreme, meaning that more than 100 lives would be lost in the event of dam failure. The Silva-Lambe-Marr method was used to estimate an annual probability of failure of 0.45% with a range 0.1-1% (1 in 1000 to 1 in 100). According to most U.S. and Canadian guidelines, the maximum annual probability of failure should be 0.001% (1 in 100,000).

EXECUTIVE SUMMARY

The Copper Mountain Tailings Management Facility in British Columbia, Canada, was operated from 1972 to 1996 and then re-activated in 2011. The facility currently stores 309 million metric tons of mine tailings within a natural valley, so that the tailings are confined by the natural topography and an East Dam and West Dam at either end of the valley. The dams are constructed by passing the tailings through cyclones and depositing the underflow (the coarser-grained tailings or sands) without compaction, while the overflow (the finer-grained tailings or slimes) is hydraulically discharged behind the dam crest. The dams are raised about five meters per year. The pre-2011 raises were a mix of centerline and upstream raises, while the post-2011 raises have used the "modified centerline" method. The distinguishing feature of the upstream construction method is that the dam is constructed on top of the uncompacted, fine-grained tailings that are being impounded. At the end of 2022 the dam crest elevation will be 973 meters above sea level, corresponding to heights of 172.5 meters and 164.5 meters for the East Dam and West Dam, respectively. The permitted elevation of 997 meters above sea level (corresponding to approximate heights of 196.5 meters and 188.5 meters for the East Dam and West Dam, respectively) will be attained in 2027. The dam failure consequence category is Extreme, meaning that more than 100 lives will be lost in the event of dam failure.

The objective of this report was to use the Silva-Lambe-Marr method to determine the annual probability of failure of the tailings dams at the Copper Mountain mine. The Silva-Lambe-Marr method is based upon a combination of the static factor of safety with the Level of Engineering. The static factor of safety is the lowest ratio of the shear strength to the applied shear stress along a failure surface, as considered over all possible failure surfaces under static conditions (absence of seismic loading). Mining regulations in British Columbia require a minimum static factor of safety of 1.5, which is standard in most of the world. In general, the Level of Engineering refers not to the current condition of the dam, but to the present and past ability of the engineering team to mitigate and remediate potential problems. The Level of Engineering has four categories, which are Best (appropriate for facilities with high failure

consequences), Above Average (appropriate for ordinary facilities), Average (appropriate for unimportant or temporary facilities with low failure consequences), and Poor (corresponding to little or no engineering and not appropriate under any circumstances). The Level of Engineering is chosen by comparing the characteristics of the tailings dam with key characteristics in the five areas of Design – Investigation, Design – Testing, Design – Analyses and Documentation, Construction, and Operations and Monitoring. In this report, the Level of Engineering was determined from information available in annual Dam Safety Inspection reports from 2014 to 2021 and in the five-year Dam Safety Review reports for 2016 and 2021.

A key theme running throughout the determination of the Level of Engineering is the distinction between the construction quality that began in 2015 and the earlier construction quality. Beginning in 2015, there have been detailed construction reports with comparisons between lab and field measurements, lab tests carried out on undisturbed specimens at field conditions, and extensive quality control. However, in Dam Safety Inspection reports, all of the above construction quality applies only to the construction (dam raise) that was carried out over the previous year, not to the tailings management facility as an entirety. By contrast, according to the 2021 Dam Safety Review, the construction material for the starter dam was "random," there is no information on the construction material prior to 1980, and the reactivation construction in 2011 did not follow the permitted design. Since the approximate heights of the East Dam and West Dam at the end of 2014 were 129.5 meters and 121.5 meters, respectively (75% and 74% of the present height), due consideration was given to the low quality of the earlier construction in the assignment of the tailings dams at the Copper Mountain mine to the appropriate Level of Engineering in this report.

According to the 2021 Dam Safety Review, there was limited investigation of the foundation upstream of the starter dams and, due to the thickness of the impounded tailings, it would be prohibitively expensive to advance this investigation at the present time. There has never been an evaluation of the design or performance of nearby structures nor an analysis of historic aerial photographs. The knowledge of the pore pressures in the foundation is hampered by a lack of piezometers that are still functioning. Based on the above, the category Above Average (score of 0.4) was chosen for Level of Engineering in the area Design – Investigation. There has been little documentation of calibration of equipment or sensors prior to testing and the use of index field tests to detect non-uniformities has been limited. There is no indication that strength tests were carried out along field effective and total stress paths or that pore pressure was measured in strength tests. Based on the above, as well as the contrast between the testing carried out before 2015 and beginning in 2015, the category Average to Above Average (score of 0.5) was chosen for Level of Engineering in the area Design – Testing.

Many of the characteristics for the area Design – Analyses and Documentation relate to the methodology for calculating the factor of safety. The only stability analyses that have been carried out for the permitted elevation calculated static factors of safety FS of FS = 1.3 and FS = 1.4 for the East Dam, which are less than the minimum value of FS = 1.5 required in British Columbia. The higher factor of safety (FS = 1.4) was based upon long-term dam behavior (after dissipation of excess pore pressure generated during construction), which is irrelevant for dams that are under continual construction. The same analyses calculated static factors of safety for the West Dam of FS = 1.3 based on a two- dimensional model and FS = 1.7 for a three-dimensional model. According to the 2021 Dam Safety Review, the three-dimensional calculation did not properly take into account the actual width of the weak glaciolacustrine layer in the foundation. The stability analysis for the West Dam did not state the assumptions that were made for the position of the water table. Later stability analyses calculated static factors of safety of FS = 1.6 and FS = 1.9 (only for long-term behavior) for the East Dam and FS = 1.6 for the West Dam. The later analyses were not carried out for the permitted elevation, but only for the elevation as it existed in 2020. According to the 2021 Dam Safety Review, the later stability analyses assumed water tables that were much lower than the earlier analyses and much lower than were justified by the piezometric data. None of the stability analyses have considered the high water table that could result from an extreme storm event, such as the Probable Maximum Flood. All of the stability analyses have assumed a density of the cycloned sands that compose the dam raises that is higher than what has been measured, which could result in a factor of safety that is either too low or too high. In summary, many aspects of the calculations of factor of safety have been based upon questionable assumptions, as opposed to measured parameters.

Other characteristics of the stability analyses preclude placement into the categories Best or Above Average in the area Design – Analyses and Documentation. There has been no consideration of the field stress path in the stability determinations nor any adjustment for differences between field stress paths and the stress paths implied in the stability analyses. There is no flow net (showing flow paths) for instrumented sections nor any predictions of pore pressures and other relevant performance parameters, such as stress deformation or flow rates at instrumented sections. Although there are numerous brief tables of design criteria, there is nothing that would be considered a detailed Design Basis Report. It is assumed that the Independent Tailings Review Board is providing peer review, although there are no records of their deliberations or recommendations. Based on the above, with special emphasis on the lack of measured parameters used for calculation of the factor of safety, the category Average (score of 0.6) was chosen for Level of Engineering in the area Design – Analyses and Documentation.

The contrast between the quality of the construction before 2015 and beginning in 2015 was a key factor in choosing the category for Level of Engineering in the area of Construction. The category Best would require full-time supervision of all construction by a qualified engineer. However, the Operations, Maintenance and Surveillance Manual clarifies that supervision by a qualified engineer occurs only for “critical” construction, and not for “routine” or “significant” construction. The category Above Average (score of 0.4) was chosen for Level of Engineering in the area Construction, which essentially splits the difference between the earlier and later construction.

The annual Dam Safety Inspection reports have documented the steady breakdown of the tailings dam instrumentation. The number of functional piezometers has varied between 37 and 46 and was at an all-time low at the end of 2021. The 2021 Dam Safety Review drew particular attention to the lack of functional piezometers and the difficulty that posed for the correct delineation of the water table for stability analyses. Out of seven inclinometers that had been installed since 2011, only one was functional at the end of 2021. The category Best would require no malfunctioning instruments, continuous maintenance by trained crews, and a complete performance program, including comparison between predicted and measured performance, in areas such as pore pressure, strength, or deformations. The category Above Average would require the correction of malfunctions. However, since the category Average would not require any field measurements, the category Average to Above Average (0.5) was chosen for Level of Engineering in the area of Operations and Monitoring.

Based upon the preceding category choices in each area of the Level of Engineering, a total score of 2.4 was determined, where Above Average would have a score of 2 and Average would have a score of 3. Using the factors of safety for the East Dam in the range 1.3-1.4

(corresponding to the permitted elevation), the annual probability of failure was estimated in the range 0.2-0.8% with a best estimate of 0.4%. Using the factors of safety for the West Dam in the range 1.3-1.7 (corresponding to the permitted elevation), the annual probability of failure of the West Dam was estimated in the range 0.004-0.8% with a best estimate of 0.05%. Since the failures of either the East Dam or West Dam will result in the failure of the entire tailings management facility, the best estimate for the annual probability of failure for the entire facility is 0.45%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.1-1% (1 in 1000 to 1 in 100).

Based upon the historical record of tailings dam failures in British Columbia from 1969 to 2015, the annual probability of failure of a tailings dam in British Columbia is 0.17% (1 in 600). Using that information alone, and since the Copper Mountain Tailings Management Facility has two tailings dams, the annual probability of failure of the tailings facility is 0.34%, which is shockingly similar to the value that was calculated using the Silva-Lambe-Marr method. The implication is that the Level of Engineering for the tailings dams at the Copper Mountain mine is simply typical for tailings dams in British Columbia. However, it should be evident that such typical engineering is not good enough for tailings dams in the failure consequence category Extreme (corresponding to loss of more than 100 lives).

An annual probability of failure in the range 0.l-1% (1 in 1000 to 1 in 100) is completely unacceptable according to Canadian and US guidelines. According to the guidelines of the Canadian Dam Association, for the minimum of 100 fatalities, marginal acceptability would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while broad acceptability would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000). Between marginal and broad acceptability is the As Low as Reasonably Practicable (ALARP) region in which the risk is acceptable only after risks to life have been reduced to the point where further risk reduction is impracticable or requires action that is grossly disproportionate in time, trouble, and effort to the reduction of risk achieved. The guidelines of the (US) Federal Energy Regulatory Commission and U.S. Army Corps of Engineers for existing dams provide the same values, but with slightly different vocabulary. The guidelines of the U.S. Army Corps of Engineers for new dams would require an annual probability of failure no greater than 0.0001% (1 in 1,000,000) to satisfy the Societal Tolerable Risk Limit, with the further requirement that risk is tolerable only if ALARP requirements have been satisfied.

Although the tailings dams are described as constructed by the "modified centerline" method, the correct terminology is "modified upstream" (which has been confirmed by the International Commission on Large Dams), since the dam raises are still constructed on top of the fine-grained, uncompacted tailings. Even so, all of the dam raises carried out between 1980 and 1996 have been explicitly described as "upstream," so that large portions of the dam are underlain by fine-grained, uncompacted tailings. The upstream construction method is the cheapest because it requires the minimal amount of construction material. The upstream construction method is also the most dangerous, since if the fine-grained tailings undergo liquefaction, the tailings dam can fail by falling into or sliding over the underlying liquefied tailings, even if the dam temporarily maintains its structural integrity. Recent studies have documented the disproportionately large representation of upstream tailings dams among tailings dam failures and tailings dams with stability issues. For the above reasons, the upstream construction method is prohibited in Brazil, Chile, Ecuador, and Peru, and the mining industry has been steadily moving away from upstream construction, even where it is not prohibited, including in British Columbia. Apologists for the upstream construction method have argued that the method is workable if there is low precipitation, low seismicity, and high-quality personnel who cannot violate even one out of ten critical rules. Such a strict need for making no mistakes should require a Level of Engineering in the category Best, rather than the category Average to Above Average that has been observed for the tailings dams at the Copper Mountain mine.

There is currently a proposal to raise the permitted elevation for the Copper Mountain Tailings Management Facility to 1060 meters above sea level, corresponding to approximate heights of 259.5 meters and 251.5 meters for the East Dam and West Dam, respectively, which would make the East Dam and West Dam the second and third tallest tailings dams in the world. It is recommended that the regulatory agencies in British Columbia move forward from their current narrow focus on the factor of safety and consider the annual probability of failure, which is a standard practice in the dam industry in Canada and the USA. No such proposal, and even no further dam raising, should be entertained until the annual probability of failure of the tailings dams can be reduced to no greater than 0.001% (1 in 100,000), and even lower as required by ALARP principles.

If all engineering from now on were elevated to the highest standards, the Level of Engineering could be increased to 1.5 or midway between Above Average and Best. The maximum future Level of Engineering is constrained by the characteristics that cannot be fixed, such as the insufficient investigation of the foundation prior to constructing the tailings management facility. Assuming the current calculated factors of safety did not change, the minimum future annual probability of failure of the East Dam was estimated in the range 0.007-0.049% with a best estimate of 0.018%, while the minimum future annual probability of failure of the West Dam was estimated in the range 0.00005-0.007% with a best estimate of 0.002%. By summing the best estimates for the East and West Dams, the best estimate for the minimum annual probability of failure of the Copper Mountain Tailings Management Facility after improvement of engineering to the highest standards would be 0.02%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.01-0.1% (1 in 10,000 to 1 in 1000) even after improvement of engineering to the highest standards, which would still be too high by at least an order of magnitude, according to US and Canadian guidelines. Further recommendations for lowering the annual probability of failure of the Copper Mountain Tailings Management Facility are not obvious and are beyond the scope of this report.

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OVERVIEW

Mine tailings are the wet and crushed rock particles that remain after the commodity of value has been removed from an ore body. The tailings from the Copper Mountain mine in southern British Columbia, Canada (see Fig. 1) are disposed of into the Copper Mountain Tailings Management Facility. The tailings management facility is located in a river valley so that the tailings are confined by the natural topography and by dams at the east and west ends of the valley (see Fig. 2). The Copper Mountain Tailings Management Facility was operated from 1972 to 1996, during which time 191 million metric tons of tailings were disposed of. The facility was reactivated in 2011 and an additional 118 million metric tons of tailings were disposed of by 2021, for a current total of 309 million metric tons of tailings (Tetra Tech, 2022).

The East and West Dams (see Figs. 3a-b) are raised each year in order to accommodate additional tailings. At the end of 2022 the dam crest elevation will be 973 meters above sea level and the permitted elevation of 997 meters above sea level will be attained in 2027 (Klohn Crippen Berger, 2021a). At present time, there is a proposal to raise the dam crest elevation to 1060 meters above sea level (Copper Mountain Mining Corporation, 2020; Klohn Crippen Berger, 2020a). Although nearly all documents refer to elevations above sea level, Tetra Tech (2022) clarifies that the approximate heights for the East Dam (vertical distance from the dam toe to the dam crest) will be 172.5 meters at the end of 2022 and 196.5 meters in 2027, with a proposed height of 259.5 meters (see Fig. 4). The approximate heights for the West Dam will be 164.5 meters at the end of 2022 and 188.5 meters in 2027, with a proposed height of 251.5 meters. By comparison, the current tallest tailings dam in the world is the Linga dam at the Cerro Verde mine in Peru with a height of 265 meters, and the tallest dam in Canada is at the Kemess South mine in British Columbia with a height of 180 meters (GRID-Arendal, 2022). Thus, the current permit will allow the East and West Dams to become the tallest and second tallest tailings dams in Canada, while the proposal would allow the East Dam to become the second tallest tailings dam in the world. The failure consequence category for the Copper Mountain Tailings Management Facility is rated as Extreme (Tetra Tech, 2022), meaning that more than 100 lives would be lost in the event of dam failure (Canadian Dam Association, 2013).

The objective of this report is to determine the annual probability of failure of the Copper Mountain Tailings Management Facility. Since the failure of either dam would constitute a failure of the facility, the annual probability of failure of the Copper Mountain Tailings Management Facility is the sum of the annual probabilities of failure of the East Dam and the West Dam. Some consideration is necessary for the meaning of the phrase "tailings dam failure." According to Canadian Dam Association (2021), "a tailings dam failure can generally be defined as the inability of the dam to meet its design intent, whether in terms of management, operational, structural, or environmental function, resulting in potential loss of life, loss to the stakeholders, or adverse environmental effects." From that standpoint, blowing dust from the tailings beach or the seepage of the tailings pore water into groundwater would constitute tailings dam failures, even with no structural damage to the tailings dam. However, this report will further follow Canadian Dam Association (2021) in restricting the consideration of tailings dam failures to "a physical breach of the dam followed by uncontrolled and typically sudden and catastrophic release of any or all stored materials (e.g., fluids, tailings, sludge, etc.)." In other words, a failure of the tailings dams is the event that would correspond to the Extreme consequence category (loss of more than 100 lives). The restriction in scope of this report does not deny that environmental impacts (such as windblown dust) can be just as disastrous to surrounding communities and ecosystems as a physical breach of the tailings dam.

Before discussing the methodology for addressing the objective, this report has four sections for review of the essential background. The first review section is a tutorial on soil and tailings mechanics with emphasis on the concept of factor of safety. The next section summarizes the Silva-Lambe-Marr method for the estimation of annual probability of failure of embankments (raised earthen structures), which will be used in this report, and locates the method within the context of the meaning of "annual probability of failure." The third review section summarizes the general methods of tailings dam construction, while the last review section is specific to the methods of tailings dam construction that have been used at the Copper Mountain mine.

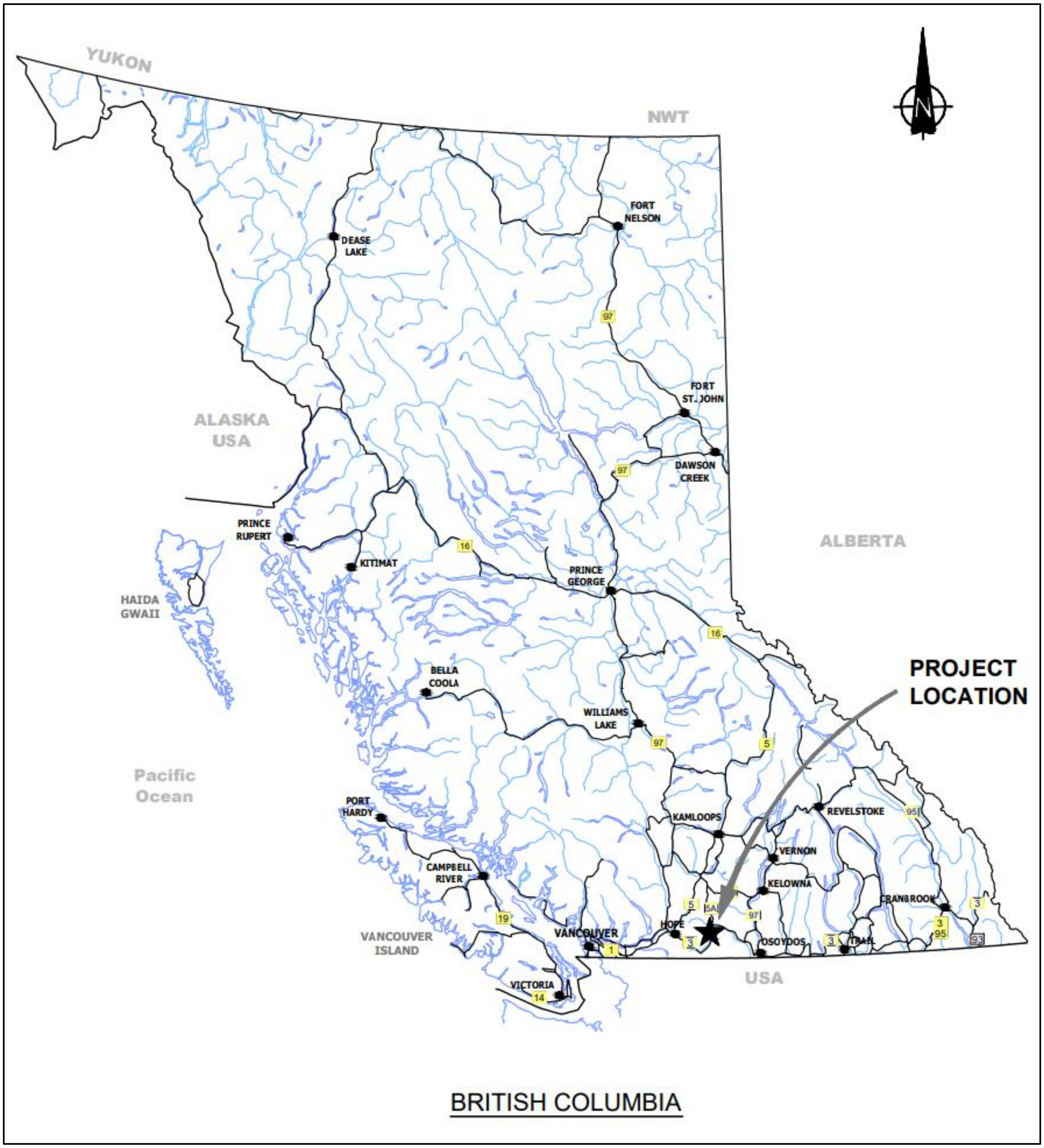


Figure 1. The Copper Mountain mine is located in southern British Columbia. Figure from Klohn Crippen Berger (2017a).

Figure 2. The Tailings Management Facility for the Copper Mountain mine is located in a natural valley so that it is confined by the natural topography to the north and south and by the East Dam and West Dam on the ends of the valley. The hydraulic discharge of tailings from the dam crests creates tailings beaches (grayish color) extending toward the interior of the tailings management facility (compare with Figs. 11 and 17a-b). The water and fine-grained tailings (slimes) are carried into the interior of the Tailings Management Facility to form a tailings pond (bluish color). Water from the tailings pond is recycled into the mining operation. Portion of figure from Klohn Crippen Berger (2017b).

TUTORIAL ON SOIL AND TAILINGS MECHANICS

From an engineering perspective, a soil is composed of solid particles in which the pores between the particles are filled with a combination of air and water. From this standpoint, a mass of mine tailings is a type of soil. From an agricultural perspective, a soil should include organic matter and organisms and be able to support the growth of higher plants. However, these biological properties are not relevant for engineering purposes. An excellent reference for more complete information on the engineering properties of soils is Holtz et al. (2011). This tutorial largely follows the presentation in Holtz et al. (2011).

Photo II-1 East Dam downstream slope looking west from the Copper Mountain Road (October 14, 2020)

Figure 3a. At the end of 2022, the crest of the East Dam will be 973 meters above sea level, corresponding to an approximate height of 172.5 meters. The permitted crest elevation of 997 meters above sea level (corresponding to an approximate height of 196.5 meters) will be achieved in 2027. Photo from Klohn Crippen Berger (2021).

Photo II-26 West Dam downstream slope looking east from toe seepage pond (October 14, 2020)

Figure 3b. At the end of 2022, the crest of the West Dam will be 973 meters above sea level, corresponding to an approximate height of 164.5 meters. The permitted crest elevation of 997 meters above sea level (corresponding to an approximate height of 188.5 meters) will be achieved in 2027. Photo from Klohn Crippen Berger (2021).

Table 3-2: Summary of Configuration of TMF Dams in 2020

	West Dam	East Dam
Crest Length	750 m	575 m
Crest Elevation (Height)	962.5 masl (~154 m)	962.5 masl (~162 m)
Downstream Slope[1]	2.5H:1V or flatter	2.1 to 2.5H:1V
Upstream Slope	3H:1V	3H:1V
Tailings Beach Width[2,3]	500 m	400 m

Notes:

1. Overall downstream slope. Local oversteepening present due to sand deposition.
2. The design slope for the above water tailings beaches is 0.5% (CMML 2020a), but the beach slope is not reported.
3. Beach width reported at the end of 2020

Figure 4. Nearly all of the available documents state the dam crest heights in terms of elevation above sea level. The table clarifies that 962.5 meters above sea level corresponds to approximate heights of 154 meters above the dam toe for the West Dam and 162 meters above the dam toe for the East Dam. Thus, at the end of 2022, the approximate heights of the East Dam and West Dam will be 172.5 meters and 164.5 meters, respectively (corresponding to 997 meters above sea level). At the permitted dam crest elevation of 997 meters above sea level, which will be achieved in 2027, the approximate heights of the East Dam and West Dam will be 196.5 meters and 188.5 meters, respectively. At the proposed dam crest elevation of 1060 meters above sea level, the approximate heights of the East Dam and West Dam will be 259.5 meters and 251.5 meters, respectively. Table from Tetra Tech (2022).

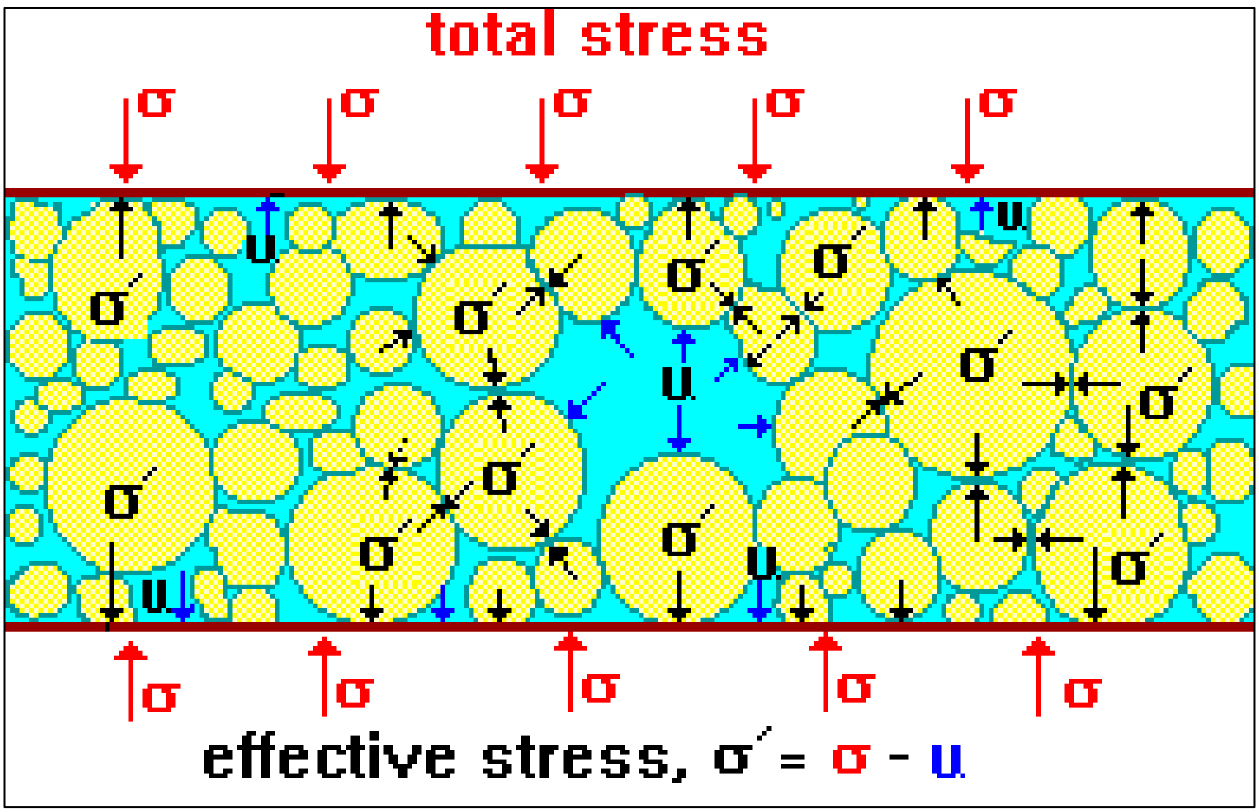


Figure 5. The effective stress in soil is equal to the total stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other. Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress. Figure from GeotechniCAL (2022).

A normal stress means any stress that is acting perpendicular to a surface (see Fig. 5). A normal stress acting on a soil can be partially counterbalanced by the water pressure within the pores. The effective stress is defined as the normal stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other (see Fig. 5). The normal stress without subtracting the pore water pressure is also called the total stress.

Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress (Holtz et al., 2011). For example, suppose that sediments are deposited on a river floodplain or tailings are hydraulically discharged into a tailings reservoir. The weight of the solid particles creates a normal stress, so that the particles will consolidate under their own weight. The amount and rate of consolidation is determined by the effective stress, that is, the extent to which the particles are interacting with each another. Sufficient water pressure can offset the normal stress, so that little consolidation could occur and at a slow rate.

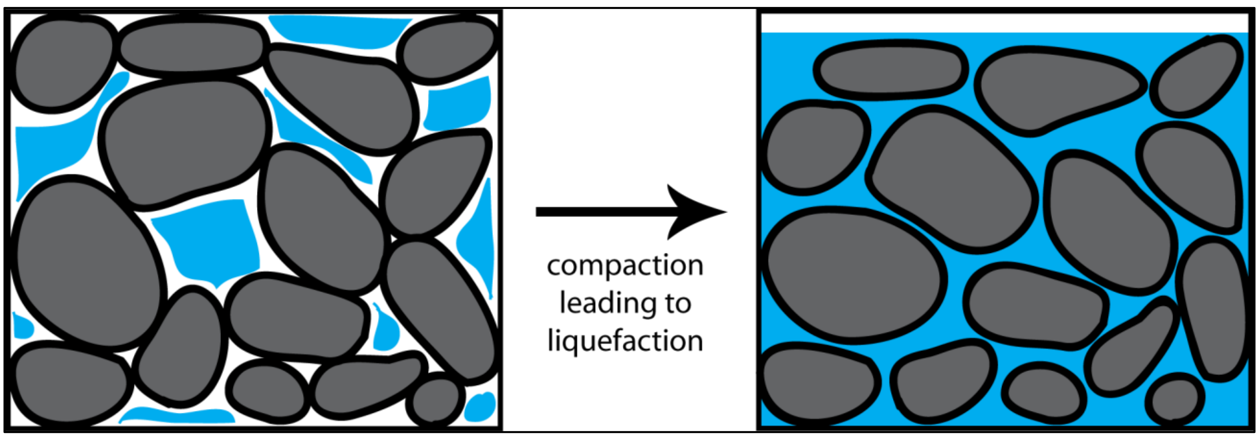


Figure 6. In the diagram on the left, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other, so that the load is supported by the particles (and partially by the water). Loose-packing means that the soil is in a contractive state, so that the solid particles will tend to compact to a more densely-packed state following an increase in load or a disturbance (such as an earthquake). If the water cannot escape (due to low permeability or the speed of the disturbance), the solids cannot compact so that the additional stress is converted into an increase in pore water pressure (see the diagram on the right). The increased water pressure can decrease the effective stress almost to zero or to the point where the particles no longer "touch" each other (see Fig. 5). At this point, the soil mass has undergone liquefaction in which the water supports the entire load and the mass of particles and water behaves like a liquid. This phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles. If the pores are unsaturated prior to the disturbance, some compaction can occur (decreasing the size of the pores), so that the pores become saturated. Any further contractive behavior will then convert the additional stress into increased pore water pressure. On that basis, liquefaction is possible even if the pores are only 80% saturated. Figure from DoITPoMS (2022).

The phenomenon of liquefaction, in which a soil loses its strength and behaves like a liquid, can be explained through an application of Terzaghi's Principle (see Fig. 6). In the diagram on the left-hand side of Fig. 6, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other. Because there is contact between the particles, the load (the weight of particles or other materials above the particles shown on the left-hand side of Fig. 6), is carried by the solid particles. The load is also partially borne by the water due to the water pressure. The term permeability refers to the ability of water to flow through the pores. A mix of coarse and fine particles will have low permeability because the finer particles will fill in the pores between the coarser particles and, thus, restrict the pore space for water flow.

Loose-packing means that the soil is in a contractive state, so that the solid particles will tend to compact to a more densely-packed state following an increase in load or a disturbance (such as an earthquake). If the water cannot escape (due to low permeability or the speed of the disturbance), the solids cannot compact so that the additional stress is converted into an increase in pore water pressure (see right-hand side of Fig. 6). The increased water pressure can decrease the effective stress almost to zero or to the point where the particles no longer "touch" each other (see Fig. 6). At this point, the soil mass has undergone liquefaction in which the water supports the entire load and the mass of particles and water behaves like a liquid.

The phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles. As will be discussed in the section Methods of Tailings Dam Construction, tailing deposits are especially susceptible to liquefaction because the tailings are very loosely-packed due to the hydraulic discharge into the tailings management facility without compaction. If the pores are unsaturated prior to the disturbance, some compaction can occur (decreasing the size of the pores), so that the pores become saturated. Any further contractive behavior will then convert the additional stress into increased pore water pressure. On that basis, liquefaction is possible even if the pores are only 80% saturated. There is a considerable literature on methods for evaluating the susceptibility of soil or tailings to liquefaction (Fell et al., 2015). For example, incomplete gravity separation during hydraulic discharge could lead to a mix of coarse and fine tailings, which could make the tailings more susceptible to liquefaction by reducing their permeability.

Soil that is already in a densely packed state is said to be in a dilative state, so that the solid particles will tend to expand following a disturbance. In this case, disturbance causes a strengthening, rather than a weakening of the soil, due to the resulting decrease in pore water pressure. A soil in which the particles will neither compact nor expand following a disturbance is said to be in the critical state. The basis of Critical State Soil Mechanics is the principle that, following a disturbance, all soils will tend to approach the critical state of packing, in which the critical void ratio (ratio of volume of pore space to volume of solid particles) depends upon the effective vertical stress.

The shear strength of soil (resistance to failure by shearing) is expressed by two parameters, called the cohesion (c) and the friction angle (φ). A common laboratory test for measuring the parameters c and φ is the triaxial test in which a soil sample is compressed in three perpendicular directions with the greatest compressive stress (denoted by σ_1) in the vertical direction and two compressive stresses (denoted by σ_3) in the two horizontal directions (see left-hand side of Fig. 7). The two horizontal compressive stresses are equal to each other and smaller than σ_1. On any plane that is inclined with respect to the principal stresses (σ_1 and σ_3), a normal stress (σ_n) occurs across or perpendicular to the plane, while a shear stress (τ) occurs along the plane. A plot of τ vs. σ_n will tend to fall on a straight line, in which the cohesion (c) is the intercept of the line on the vertical τ-axis and the tangent of the friction angle (φ) is the slope of the line (see right-hand side of Fig. 7). The Mohr circle is a circle with center on the horizontal σ_n-axis at $(\sigma_1 + \sigma_3)/2$ and radius $(\sigma_1 - \sigma_3)/2$. According to the Mohr-Coulomb theory of failure, the soil sample will fail when the Mohr circle touches the straight line. The shear stress at the point where the Mohr circle touches the straight line is the shear stress at the point of failure, denoted by τ_f, also known as the shear strength. Larger values of c and/or φ correspond to greater shear strength, in that a larger difference between the principal compressive stresses ($\sigma_1 - \sigma_3$) is required to cause failure. Note that the friction angle is not a physical angle, but only an angle on the plot of τ vs. σ_n.

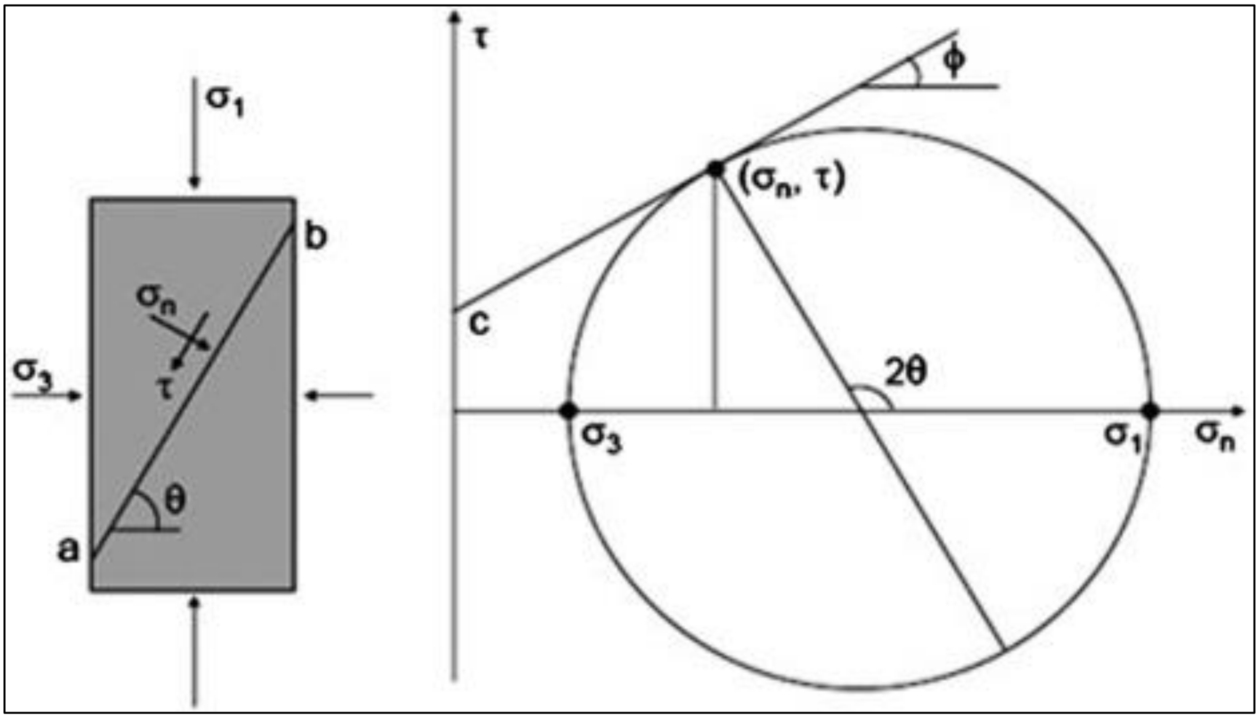


Figure 7. In the diagram on the left, a soil sample is compressed in a laboratory test with the greatest compressive stress (σ_1) in the vertical direction and the least compressive stress (σ_3) in the horizontal direction. On any plane that is inclined with respect to the principal stresses (σ_1 and σ_3), a normal (or perpendicular) stress (σ_n) occurs across the plane, while a shear stress (τ) occurs along the plane. A plot of τ vs. σ_n will tend to fall on a straight line, in which the cohesion (c) is the intercept of the line and the tangent of the friction angle (φ) is the slope of the line (see diagram on the right). The Mohr circle is a circle with center on the σ_n-axis at $(\sigma_1 + \sigma_3)/2$ and radius $(\sigma_1 - \sigma_3)/2$. According to the Mohr-Coulomb theory of failure, the soil sample will fail when the Mohr circle touches the straight line. The values c and φ are the shear strength parameters, in which larger values of c and/or φ correspond to greater shear strength. The same plots can be made with effective stress (see Fig. 5) on the horizontal axis, in which case a different set of shear strength parameters are obtained, denoted as c′ and φ'. The primed variables (based on effective stress) are appropriate when experiments are conducted under drained conditions, when pore water is free to escape from the soil sample. The corresponding field condition would be slow disturbance and/or unsaturated pores. The unprimed variables (based on total stress) are appropriate when experiments are conducted under undrained conditions, when the soil sample is sealed so that pore water cannot escape. The corresponding field condition would be rapid disturbance and/or saturated pores. Figure from Bejarbaneh et al. (2015).

Laboratory shear strength testing can be carried out under either drained or undrained conditions. In the drained condition, water is free to escape from the soil sample as the sample is compacted in response to the compressive stress σ_1. In accordance with Terzaghi's Principle, the amount of compaction is due to the increase in effective stress, which is the increase in the compressive stress σ_1 minus the water pressure. For drained tests, τ is plotted against the effective stress, denoted as σ_n'. A plot of τ vs. σ_n' yields a different straight line (different from a plot of τ vs. σ_n) with cohesion c′ (intercept with the vertical τ-axis) and friction angle φ' (where the tangent of the friction angle is the slope of the line). The primed variables c′ and φ' indicate measurement with respect to effective stress.

In laboratory shear strength tests under the undrained condition, the soil sample is sealed so that water cannot escape from the pores between the solid particles. Since water cannot escape, the soil sample can be compressed by the external stresses (see left-hand side of Fig. 7), but it cannot be compacted. In accordance with Terzaghi's Principle, no compaction or consolidation corresponds to no increase in effective stress. This means that all increases in normal stress are converted into increases in pore water pressure, so that the effective stress remains constant. Under these conditions, the failure of the soil sample is determined by the total stress, not the effective stress. For the undrained condition, a plot of τ vs. σ_n yields the shear strength parameters c and φ, in which the unprimed variables indicate measurement with respect to total stress (see Fig. 7). An alternative shear strength parameter that is often used under undrained conditions is the undrained shear strength ratio, which is the undrained shear strength (maximum shear stress before sample failure) divided by the effective vertical stress.

Each of the laboratory testing conditions corresponds to a particular field situation (such as a tailings dam). The field situation corresponding to laboratory drained testing would be some combination of slow disturbance, high soil permeability, and unsaturated pores. Under the above conditions, water would be free to escape as the soil was compressed or sheared. The field situation corresponding to laboratory undrained testing would be some combination of rapid disturbance, low soil permeability, and saturated pores. Under the above conditions, water would not be free to escape as the soil was compressed or sheared, so that pore water pressure would increase in response to a disturbance (such as an earthquake).

Although the shear strength parameters arise from laboratory tests, it is not generally recommended to rely on laboratory tests alone for the mechanical properties of the tailings dam, tailings and foundation materials. The reason is that it is quite difficult to obtain undisturbed samples, so that the mechanical properties in the laboratory can differ from the mechanical properties in the field. In addition, the field mechanical properties can depend upon larger structural features such as cracks or boulders, which would not be recovered in small samples extracted for use in the laboratory. The usual procedure is to rely on field tests and then to use empirical relationships to calculate the shear strength parameters from the results of the field tests (Holtz et al., 2011; U.S. Department of Transportation, 2017). One of the simplest field tests is the Standard Penetration Test (SPT) in which a standard sampler is driven by a 63.5-kilogram hammer falling 0.76 meters. The number of blows required to drive the sampler a distance of 0.3 meters is called the blow count or the standard penetration resistance. Another common field test is the Cone Penetrometer Test (CPT), in which a 60° cone (with a projected area of 10 square centimeters) is pushed downward at 1 to 2 centimeters per minute while the point resistance and friction on the sleeve are measured. A third example is the Vane Shear Test (VST), in which a four-bladed vane is rotated and the maximum torque is measured. Both lab and field tests that are used for indirect measurement of the shear strength parameters are collectively known as index tests. The optimum procedure is generally regarded as a combination of index field tests together with the careful collection of samples with minimal disturbance, followed by running lab tests under simulated field conditions.

The shear strength parameters can be used in a dam stability analysis, which determines the tendency of a dam to fail by sliding (or shearing or slumping). The input parameters for a stability analysis are the densities and shear strength parameters for all of the materials that make up the tailings dam, the tailings reservoir, and the foundation, as well as the geometry of the structure and the pore water pressures, including the position of the water table within the structure. The appropriate shear strength parameters (c or c′, φ or φ') depend upon whether a particular material is expected to behave in a drained or undrained condition. For example, a clay foundation with a high water table would normally be expected to behave in the undrained condition.

A stability analysis produces a factor of safety FS, which is the ratio of the shear strength of the dam to the shear stress acting on the dam, so that FS = 1.00 indicates a dam on the cusp of failure (Fell et al., 2015). In the limit equilibrium computational method, failure is assumed to occur by one rigid block sliding over another and the average factor of safety is computed along all possible failure surfaces. Some software assume that failure surfaces must be circular, but this assumption is not necessary. The failure surface with the lowest value of the factor of safety is regarded as the critical failure surface along which failure is most likely to occur and its value of factor of safety is regarded as the factor of safety of the dam. A static stability analysis evaluates the tendency of a dam to fail by sliding under its own weight without any external disturbances, such as an earthquake. The response of a dam to an earthquake is simulated by a pseudo-static analysis in which the earthquake is replaced with a horizontal force equal to the design seismic acceleration times the mass of the dam times a seismic coefficient (which accounts for the reduction in acceleration that occurs when seismic waves interact with materials softer than bedrock).

It is important to note that a stability analysis is not the same as a risk analysis or risk assessment (Vick, 2002; Morrison and Byler, 2022). A risk analysis considers all possible modes of dam failure, not only failure by sliding. For example, a tailings dam could fail by overtopping, in which water flows over the outer embankment, causing the dam to erode away. Another mode of failure is internal erosion, in which water flowing through the dam washes solid particles out of the dam, causing the dam to lose its structural integrity. A stability analysis does not evaluate the preceding failure modes, nor does it assess the circumstances under which the dam will undergo liquefaction. A stability analysis also regards a tailings dam as only a physical object, whereas a risk analysis takes into account the human factors of how the dam is designed, constructed, operated and maintained.

Table 7-9: HSRC Minimum Factors of Safety for Slope Stability – Static Assessment

Loading Condition	Minimum Factor of Safety	Slope
End of Construction (short-term)	1.5	Downstream
Long Term (steady state seepage, normal reservoir level)	1.5	Downstream
Full or partial rapid drawdown[1]	1.5	Upstream slope where applicable

Notes:
1. Does not apply to CMM TMF as pond is kept several hundred meters from upstream slope and supernatant pond water is continuously pumped out of the pond for use in ore processing.

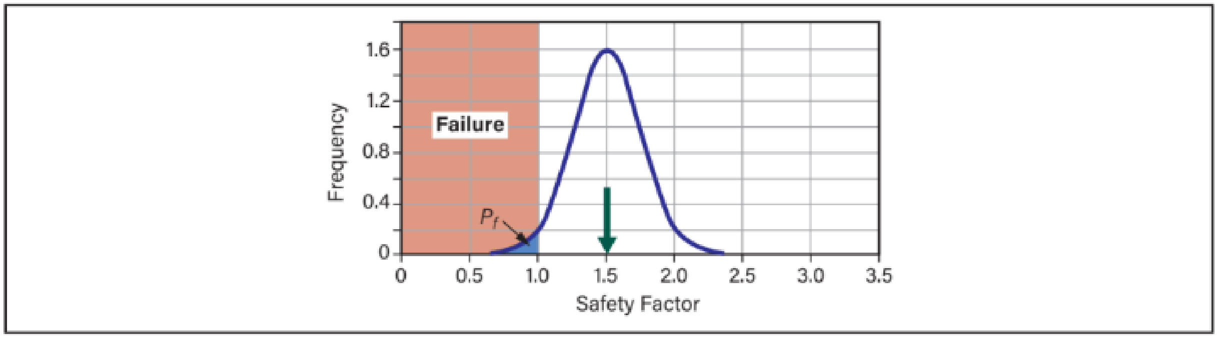
Figure 8. Mining regulations in British Columbia ((Ministry of Energy and Mines (British Columbia), 2016) require a minimum static factor of safety FS = 1.5. The static factor of safety FS is the lowest ratio of the shear strength to the applied shear stress on a failure surface, as considered over all possible failure surfaces, so that FS = 1.0 indicates a tailings dam on the cusp of failure. The static factor of safety does not consider seismic loading. The minimum FS = 1.5 is common in Canada (Canadian Dam Association, 2013, 2019), the USA (USACE, 2003; USBR, 2011) and other countries (Fell et al., 2015). Figure from Tetra Tech (2022).

Mining regulations in British Columbia establish FS = 1.5 as the minimum static factor of safety for a tailings dam (see Fig. 8; Ministry of Energy and Mines (British Columbia), 2016). The minimum value of FS = 1.5 is widely followed in Canada (Canadian Dam Association, 2013, 2019), the USA (USACE, 2003; USBR, 2011), and much of the rest of the world (Fell et al., 2015) for both tailings dams and water-retention dams. Some regulations and guidance documents allow a lower factor of safety (typically FS = 1.3) at the end of construction with a minimum FS = 1.5 over the long term, meaning, once a dam has achieved steady-state seepage at the normal level of the tailings or reservoir. The reasoning is that construction can involve a build-up of pore pressure, which lowers the effective strength and, thus, the factor of safety of the dam. The normal operation of the dam then allows the dissipation of excess pore pressure, resulting in an increase in effective strength and factor of safety. For example, in a tailings management facility, tailings might be emplaced on top of previously-deposited tailings that have not yet fully compacted, causing an increase in pore pressure in the older tailings. However, British Columbia does not make this distinction in its regulations and requires a minimum FS = 1.5 throughout construction and operation of a tailings dam (see Fig. 8). It should be noted that long-term or steady-state conditions are irrelevant to tailings dams, such as the tailings dams at the Copper Mountain mine, that are under continuous construction.

It cannot be overemphasized that the factor of safety is not an actual measurement, but the output of a model, which depends upon a wide range of assumptions and measurements, all of which have various degrees of uncertainty. In particular, the shear strength parameters and pore pressures can be highly spatially variable, although they can be measured at only a limited number of locations. For this reason, many guidance documents critique an overreliance on the factor of safety as a measure of risk and especially critique dam safety improvement programs for which the sole focus is to raise the factor of safety.

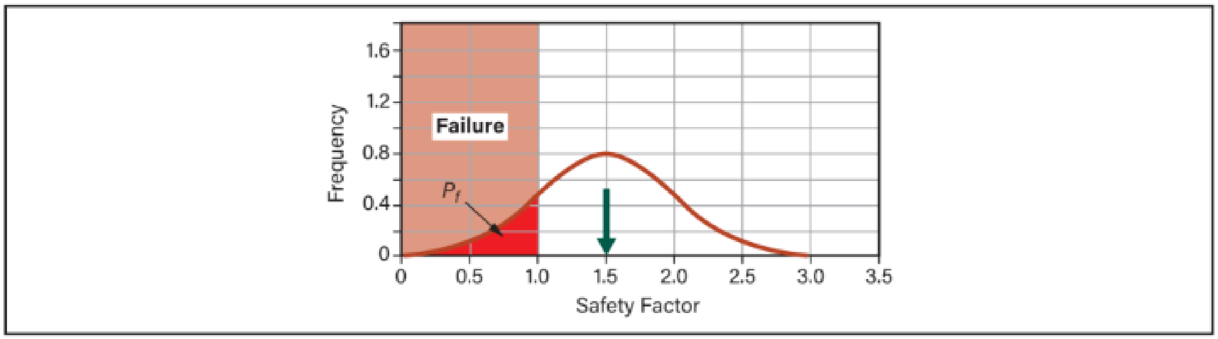
For example, the International Council on Mining & Metals (ICMM) Tailings Management—Good Practice Guide defined the Prescriptive Approach as one that "applies prescribed criteria, such as Factor of Safety, to assess the margin of safety against shear failure but is not able to address complex or dynamic design considerations, such as the risk of brittle failure and the magnitude of seismic deformations" (ICMM, 2021). ICMM (2021) continued, "In its basic form, the approach often uses a prescribed Factor of Safety (FoS) as a criterion that is perceived by some to denote whether or not a tailings facility is safe. Due to the seemingly straightforward application of FoS, it has broad appeal … A FoS is often misinterpreted as a sole measure of safety. It is based on the premise that a higher FoS reduces the likelihood of failure. However, a FoS is not a measurable value; it is an outcome based on inputs which are derived by the designer based on site data, laboratory testing and modelling. Natural variations in site and laboratory data give rise to uncertainty around the calculated FoS. However, FoS values are rarely reported with uncertainty limits. Further, a given value of FoS has an entirely different meaning if an identical value exists for both a site with a brittle credible failure mode and one with only non-brittle credible failure modes … Recent experience has highlighted the challenges associated with selecting the appropriate FoS to prevent failure in a variety of facility configurations. Instead of specifying fixed values, this Guide favours the selection of site-specific design criteria based on the evaluation of site complexity by means of the EOR [Engineer of Record] (in accordance with applicable legal requirements) and notes that the following particularly complex circumstances should be recognised: … • Potential for brittle failure." In the above quote, brittle failure modes refer to failure modes that occur without precursors, such as liquefaction, such that there will be no time to carry out corrective actions in response to adverse observations. Copper Mountain Mining Corporation is not a Company Member of ICMM, but relevant Association Members include Canada Mining Innovation Council (CMIC), International Copper Association (ICA), International Wrought Copper

Council (IWCC), Mining Association of Canada, and Prospectors and Developers Association of Canada (PDAC) (ICMM, 2022).



Source: Laccase-Höeg and Höeg 2019

FIGURE 27.2 Probability of failure based on small variability of factor of safety



Source: Laccase-Höeg and Höeg 2019

FIGURE 27.3 Probability of failure based on larger variability of factor of safety

Figure 9. Without any other information, the most-likely value of the factor of safety FS is a poor indication of the probability of failure, where the probability of failure could be understood as the probability that the true value FS < 1.0. For a given most-likely value of FS, a greater uncertainty in the value implies a greater probability that the true value FS < 1.0. In fact, a large value of FS with a high uncertainty could imply a greater probability of failure than a small value of FS with a low uncertainty. The factor of safety has no time component, so that the above probability of failure is an event probability, rather than an annual probability. Figure from van Zyl (2022).

Based on the above, the factor of safety should not be understood as a single value, but as the mean or expected value of a distribution of possible values that reflect the possible values of all of the input parameters (see Fig. 9). In this sense, the probability of dam failure (the probability that the true value of the factor of safety FS is less than 1.0), is the area under the distribution curve in the range FS < 1.0 (see Fig. 9). A value FS = 1.0 (cusp of failure) could be interpreted to mean that the dam is marginally safe, but a better interpretation is that the probability of failure (the probability that the true value of the factor of safety FS is less than 1.0) is 50%. The width of the distribution of possible values of the factor of safety depends upon the uncertainty in the input parameters. Thus, two dams with identical factor of safety do not have the same probability of failure. The dam with greater uncertainty in the input parameters will have a greater area under the distribution curve in the range FS < 1.0 and, therefore, a higher probability of failure (see Fig. 9). It is possible to imagine many situations in which a dam with a lower factor of safety with less uncertainty has a lower probability of failure than a dam with a higher factor of safety but with greater uncertainty (see Fig. 9).

In the preceding discussion, the probability of failure refers to the event probability, not the annual probability of failure, or the probability of failure within a given year. The event probability has no time component, just as the factor of safety has no time component. For example, the event probability might be the probability that dam failure will occur in a response to another event, such as an earthquake. The concept of annual probability of failure is explored in the next section.

REVIEW OF ANNUAL PROBABILITY OF FAILURE

There are three important approaches to the estimation of the annual probability of failure of dam. The first approach is the use of mathematical models. Some models relate the uncertainty in the input parameters to the uncertainty in the factor of safety and are usually more relevant for the estimation of event probabilities, rather than annual probabilities of failure. Mathematical models that can estimate the annual probability of failure are mostly limited to the frequencies of floods and seismic events, so that they are useful only for estimating the annual probability of failure due to overtopping or seismic liquefaction. It is generally agreed that, at the present time, there are no workable models for estimating the annual probability of failure due to internal erosion or static liquefaction.

The second approach is to estimate the annual probability of tailings dam failure based upon the historical record. This approach is hampered by incomplete databases for tailings dam failures, as well as existing tailings dams, including when those tailings dams were constructed. To some degree, the annual probability of tailings dam failure can be estimated within a given jurisdiction. To some degree, the annual probability of tailings dam failure can be estimated on a global basis for broad categories of dam construction methods. However, it is difficult to be any more specific based upon the characteristics of some particular tailings dam of interest. It is interesting that the most accurate estimation of annual probability of tailings dam failure based upon the historical record has been carried out for tailings dams in British Columbia as part of the investigation into the failure of the tailings dam at the Mount Polley mine (Independent Expert Engineering Investigation and Review Panel, 2015a-b). The estimation based upon the historical record in British Columbia will be compared with the estimation based upon the characteristics of two particular tailings dams in British Columbia (the tailings dams at the Copper Mountain mine) in the Discussion section.

The estimation based upon the historical record is useful in that it sets a baseline for which a qualified engineer could make a subjective judgment as to whether a particular tailings dam is more or less safe than a typical tailings dam. Subjective judgment is the third approach to the estimation of the annual probability of dam failure and it is the dominant approach at the present time. From this perspective, it can be seen that annual probability of failure has no objective reality and is not a measurement that can be made, such as a shear strength parameter. In fact, annual probability of failure could be defined as the subjective judgment of a qualified and rational engineer as to the probability that a dam will fail during a given year.

The concept of annual probability of failure as a subjective judgment should not be understood in any pejorative sense. Vick (2002), Silva et al. (2008) and many others have documented the dominance and the reliability of subjective judgment over many decades. For example, according to Vick (1994), “Subjective probability assessment by solicitation of expert opinion is not new, and its legitimacy is generally accepted." According to Morgenstern (1995), "Fig. 11 presents an attempt to organize the various data streams that enter into a QRA [Quantitative Risk Assessment] in different ways. The first distinction is between objective and subjective data. Objective data arise from observation while subjective data arise from belief, usually based on expert opinion. Objective data might be regarded as inherently superior to subjective data, but this is not necessarily true." According to Gilbert and McGrath (1996), ". . . the probability of an event might be simply a subjective measure of the degree of belief an engineer has in a judgment or prediction." According to Stewart (2000), "What we in the dam business, and indeed also in many aspects of hazardous industries outside the dam business, must employ to define uncertainty by means of probabilities are subjective processes. You may discover that 'subjective probability' is the predominant approach quoted in the literature for risk based dam assessments over the past decade or so."

The problem with the estimation of annual probability of dam failure by subjective judgment is that it is difficult for an individual engineer, no matter how qualified, to act without bias, so that individual judgments can be difficult to defend. As a consequence, subjective judgments are typically carried out by teams, so that team members can challenge one another's judgments and possible biases and arrive at a consensus. Over the past few decades, a considerable art and science has developed as to how to elicit opinions and reach consensus among teams of dam safety experts (Vick, 2002; ICOLD, 2005; Morrison and Byler, 2022). Although widely practiced, especially among federal agencies in the USA, the problem with the team approach has been the time and expense, as well as the limited number of experts with deep experience in dam safety.

This report will follow the individual approach to the estimation of annual probability of dam failure by subjective judgment that was pioneered by Silva et al. (2008), and which is known as the Silva-Lambe-Marr method. The genius of Silva et al. (2008) was to codify the subjective judgment of dam safety experts into a checklist that could be carried out by an individual qualified engineer, even one without deep experience in dam safety. Silva et al. (2008) assembled complete data from 75 engineering projects spanning over four decades, including water-retention embankment dams, tailings dams, natural and cut slopes, and some earthen retaining structures. These projects were presented to panels of experts who reached consensus on the annual probability of failure of each project and explained their reasoning.

The result was that the annual probability of failure could be estimated based upon the static factor of safety and what Silva et al. (2008) called the Level of Engineering (see Fig. 10). The Level of Engineering is composed of five areas, which are Design – Investigation, Design – Testing, Design – Analyses and Documentation, Construction, and Operation and Monitoring (see Tables 1a-e). Each area includes a checklist of various characteristics that can be used to assign a dam to a Level of Engineering in one of four categories. Category I (Best) would be appropriate for "facilities with high failure consequences" (Silva et al., 2008). Category II (Above Average) would be appropriate for "ordinary facilities" (Silva et al., 2008). Category III (Average) would be appropriate for "unimportant or temporary facilities with low failure consequences" (Silva et al., 2008), while Category IV (poor) reflects "little or no engineering" (Silva et al., 2008) and would not be appropriate under any circumstances.

In general terms, the Level of Engineering refers not to the current condition of the dam, but to the ability of the engineering, construction, and operational teams to anticipate and mitigate problems. For example, none of the characteristics refer to observations, such as muddy seepage from the dam face, which could indicate the initiation of internal erosion. In the area of

Design – Investigations, Best practice would involve a determination of the site geologic history (see Table 1a). In the area of Design – Testing, Best practice would involve running lab tests on undisturbed specimens at field conditions (see Table 1b). In the area of Design – Analyses and Documentation, Best practice would involve calculating the factor of safety using measured shear strength parameters, as opposed to assumed shear strength parameters or parameters calculated from index tests (see Table 1c). In the area of Construction, Best practice would involve full-time supervision by a qualified engineer (see Table 1d). In the area of Operations and Monitoring, Best practice would involve no malfunctioning instrumentation (see Table 1e).

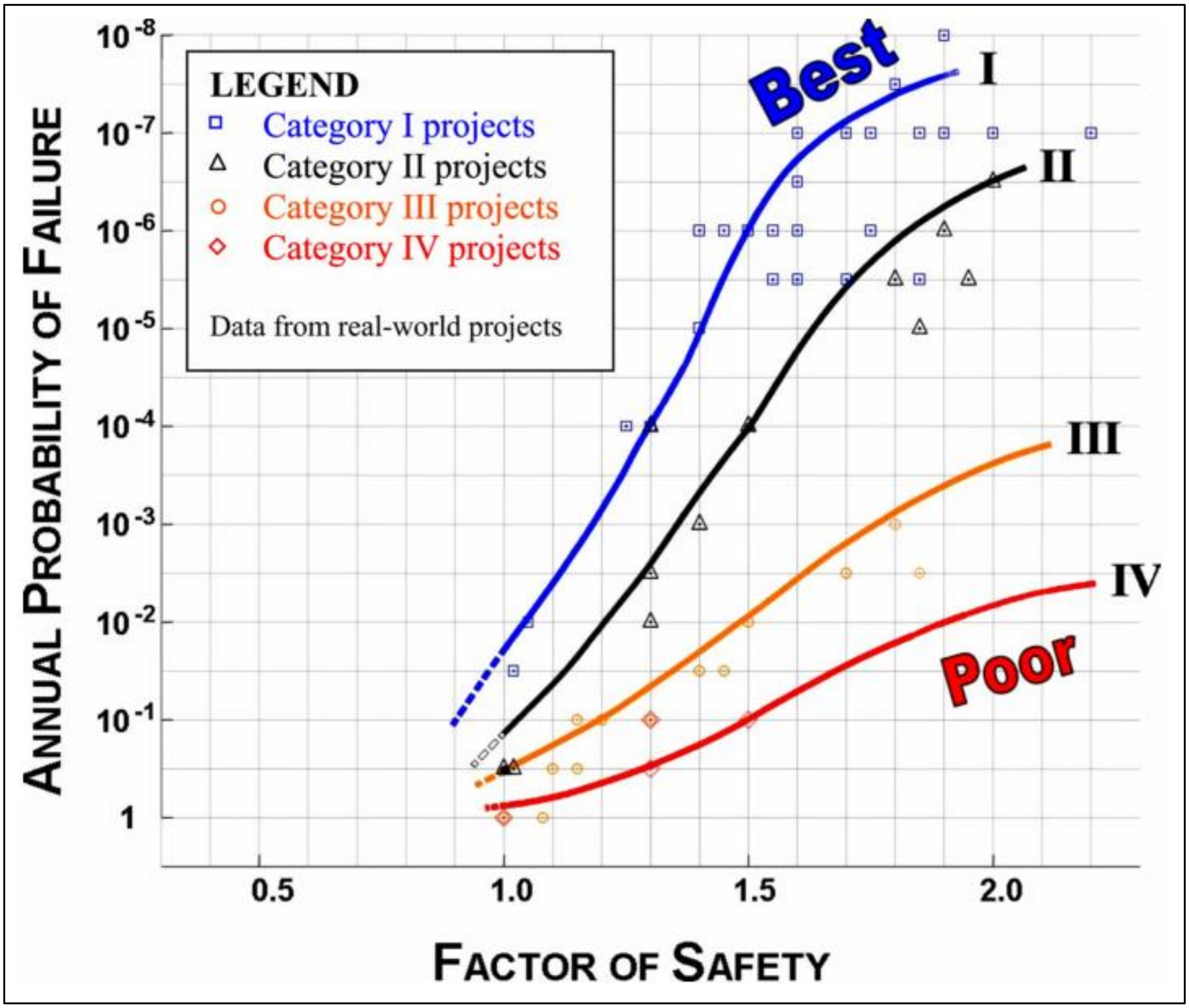


Figure 10. The Silva-Lambe-Marr method combines the factor of safety with the Level of Engineering to estimate the annual probability of failure. The four Levels of Engineering are Category I: Best (appropriate for facilities with high failure consequences), Category II: Above Average (appropriate for ordinary facilities), Category III: Average (appropriate for unimportant or temporary facilities with low failure consequences), and Category IV: Poor (implying little or no engineering and not appropriate under any circumstances). The Level of Engineering is deduced from compliance or non-compliance with key characteristics in the five areas of Design – Investigation, Design – Testing, Design – Analysis and Documentation, Construction, and Operations and Monitoring (see Tables 1a-e and 2a-e). Figure from Silva et al. (2008).

Table 1a. Current Level of Engineering (Design – Investigation) for tailings dams at Copper Mountain mine: ABOVE AVERAGE (0.4)[1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Evaluate design and performance of nearby structures	Evaluate design and performance of nearby structures	Evaluate performance of nearby structures	No field investigation
Analyze historic aerial photographs	Exploration program tailored to project conditions by qualified engineer	Estimate subsoil profile from existing data and borings	
Locate all nonuniformities (soft, wet, loose, high, or low permeability zones)			
Determine site geologic history			
Determine subsoil profile using continuous sampling			
Obtain undisturbed samples for lab testing of foundation soils			
Determine field pore pressures			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled or unknown, green = fulfilled

In the previous section, it was emphasized that factor of safety is the output of a model, not a measurement. The factor of safety could be calculated as the most-likely value, based upon the most-likely values of the input parameters. As an alternative, the factor of safety could be calculated in a "conservative" manner, in which "conservative" refers to the usual engineering sense of protective of people, property, and the environment. Thus, a conservative calculation would seek to choose the most unfavorable, but still reasonable, values of the input parameters in order to minimize the factor of safety and, thus, draw attention to the danger of failure. However, the Silva-Lambe-Marr method requires the most-likely value of the factor of safety. Otherwise, there would be a conflation of the factor of safety with the Level of Engineering, since many of the characteristics refer to the uncertainty in the factor of safety. According to Silva et al. (2008), "The strength determination corresponds to the best estimate of the strength acting in the field and not necessarily the average strength or a 'conservative' value of strength."

Table 1b. Current Level of Engineering (Design – Testing) for tailings dams at Copper Mountain mine: AVERAGE to ABOVE AVERAGE (0.5) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Run lab tests on undisturbed specimens at field conditions	Run standard lab tests on undisturbed specimens	Index tests on samples from site	No laboratory tests on samples obtained at the site
Run strength test along field effective and total stress paths	Measure pore pressure in strength tests		
Run index field tests (e.g., field vane, cone penetrometer) to detect all soft, wet, loose, high, or low permeability zones	Evaluate differences between laboratory test conditions and field conditions		
Calibrate equipment and sensors prior to testing program			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled or unknown, green = fulfilled

The publication of Silva et al. (2008) provoked a lively discussion in the Journal of Geotechnical and Geoenvironmental Engineering (Alperstein, 2010; Schmertmann and Filz, 2010; Vanden Berge and Esser, 2010), especially in terms of the meaning of an "Average" Level of Engineering. According to Vanden Berge and Esser (2010), "Category III is labeled Average in Table 1 of the original paper, which seems to contradict the accompanying description and the level of engineering … The average should lie between categories II and III, and the discussers suggest changing Category III to 'below average,' as has been done in Table 1 of this discussion." Many aspects of Category III (Average) do seem to be quite substandard. For example, the area of Construction could involve only "informal construction supervision" (see Table 1d; Silva et al., 2008) and the area of Operations and Monitoring could include "no field measurements" (see Table 1e; Silva et al., 2008).

Table 1c. Current Level of Engineering (Design – Analyses and Documentation) for tailings dams at Copper Mountain mine: AVERAGE (0.6) [1,2,3]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Determine FS using effective stress parameters based on measured data (geometry, strength, pore pressure for site)	Determine FS using effective stress parameters and pore pressures	Rational analyses using parameters inferred from index tests	Approximate analyses using assumed parameters
Consider field stress path in stability determination	Adjust for significant differences between field stress paths and stress path implied in analysis that could affect design		
Prepare flow net for instrumented sections			
Predict pore pressure and other relevant performance parameters (e.g., stress, deformation, flow rates for instrumented section)			
Have design report clearly document parameters and analyses used for design			
No errors or omissions			
Peer review			

[1]Table adapted from Silva et al. (2008)
[2]FS = Factor of safety
[3]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

The response by Silva et al. (2010) was that "Average" should not be understood as "good enough" for any particular engineering project, but rather as "typical," as considered across all engineering projects, most of which have low failure consequences. According to Silva et al. (2010), "Sadly, we agree with Messrs. Vanden Berge and Esser that the average level of engineering should lay above our Category III, but would not relabel Category II as 'average' at this time. We found the characteristics defined in Category III to more closely align with what we see as typical geotechnical practice on the 'project down the street.' Based on our collective experience we felt there are two levels of practice above 'average.' 'Above average' projects are those where engineers go above the normal and the ordinary and expend extra effort and money because the consequences of poor performance are significant to the project owner. A typical firm might do a few of these projects a year. Then there are those requiring 'best' practices where the consequences of poor performance are very large. Typical firms might work on one of these projects every decade. These are projects like nuclear power plants, major dams, and foundations for tall buildings, that call upon the best we can bring to the table to minimize risk for the least cost." The focus in this report will not be upon whether the Level of Engineering at the Copper Mountain mine is appropriate for typical engineering projects, but whether it is appropriate for projects for which "the consequences of poor performance are very large … like major dams" (Silva et al., 2010).

Table 1d. Current Level of Engineering (Construction) for tailings dams at Copper Mountain mine: ABOVE AVERAGE (0.4) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Full time supervision by qualified engineer	Part-time supervision by qualified engineer	Informal construction supervision	No construction supervision by qualified engineer
Construction control tests by qualified engineers and technicians	No errors or omissions		No construction control tests
No errors or omissions			
Construction report clearly documents construction activities			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

In the Silva-Lambe-Marr method, it is not necessary for all of the areas to correspond to the same Level of Engineering. In that case, each of the five areas has equal weighting for determination of the overall category for the dam. For example, the area of Design – Investigation might correspond to Category II (Above Average) for a score of 0.4 (see Table 1a). The area of Design – Testing might correspond to Category III (Average) for a score of 0.6 (see Table 1b). The area of Design – Analyses and Documentation might correspond to Category III (Average) for a score of 0.6 (see Table 1c). The area of Construction might correspond to Category II (Above Average) for a score of 0.4 (see Table 1e). The area of Operation and Monitoring might correspond to Category III (Average) for a score of 0.6 (see Table 1e). The total score would then be 2.6, which would be between Above Average or Category II (score = 2.0) and Average or Category III (score = 3.0), and slightly closer to Average.

Table 1e. Current Level of Engineering (Operation and Monitoring) for tailings dams at Copper Mountain mine: AVERAGE to ABOVE AVERAGE (0.5) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength, deformations)	Periodic inspection by qualified engineer	Annual inspection by qualified engineer	Occasional inspection by non-qualified person
No malfunctions (slides, cracks, artesian heads)	No uncorrected malfunctions	No field measurements	No field measurements
Continuous maintenance by trained crews	Selected field measurements	Maintenance limited to emergency repairs	
	Routine maintenance		

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

In such cases, the annual probability of failure is calculated by a linear interpolation between the values for each category for a given factor of safety, taking into account that the y-axis (annual probability of failure) is logarithmic (see Fig. 10). For example, for a factor of safety FS = 1.5, the annual probability of failure for a Category III project would be 10^{-2} or 1% (see Fig. 10). The annual probability of failure for a Category II project would be 10^{-4} or 0.01% (see Fig. 10). Thus, the annual probability of failure for a project with an overall category of 2.6 would be $10^{-3.2}$ or 0.50%.

Some proposed modifications to the Silva-Lambe-Marr method have involved keeping the general framework but adding new areas and characteristics or changing the weighting of the areas (Vanden Berge and Esser, 2010; Altarejos-García et al., 2015; Oboni and Oboni, 2020; Chovan et al., 2021). For example, Vanden Berge and Esser (2010) combined the area of Construction and the area of Operation and Monitoring into a single area called Implementation and added the new area of Owner Influence. Owner Influence ranged from the Best practice of a "sophisticated owner [who] possesses technical background or retains independent engineering advisor" and in which "safety and performance criteria dominate all decision making" to the Poor practice of an "uninformed owner indifferent to technical aspects of project" and in which "cost control dominates decision making" (Vanden Berge and Esser, 2010). Chovan et al. (2021)

modified the Silva-Lambe-Marr method so that it was specific to tailings dams and took into account the advances in practice that had taken place over the intervening decade. The scheme of Chovan et al. (2021) involved 45 criteria grouped into six Levels of Practice, which were Design – Investigation, Design – Laboratory Testing, Design – Analysis and Documentation, Construction Management and Quality Assurance / Quality Control, Operation and Monitoring, and Performance. All of the proposed modifications are very interesting in terms of checklists for what dam operators ought to be doing and are probably useful for auditing or self-auditing purposes. However, none of the proposed modifications have included the calibration by Silva et al. (2008) in which complete data on 75 projects were provided to expert panels. Therefore, at the present time, only the original Silva-Lambe-Marr method (Silva et al., 2008, 2010) should be regarded as useful for the quantitative estimation of the annual probability of failure.

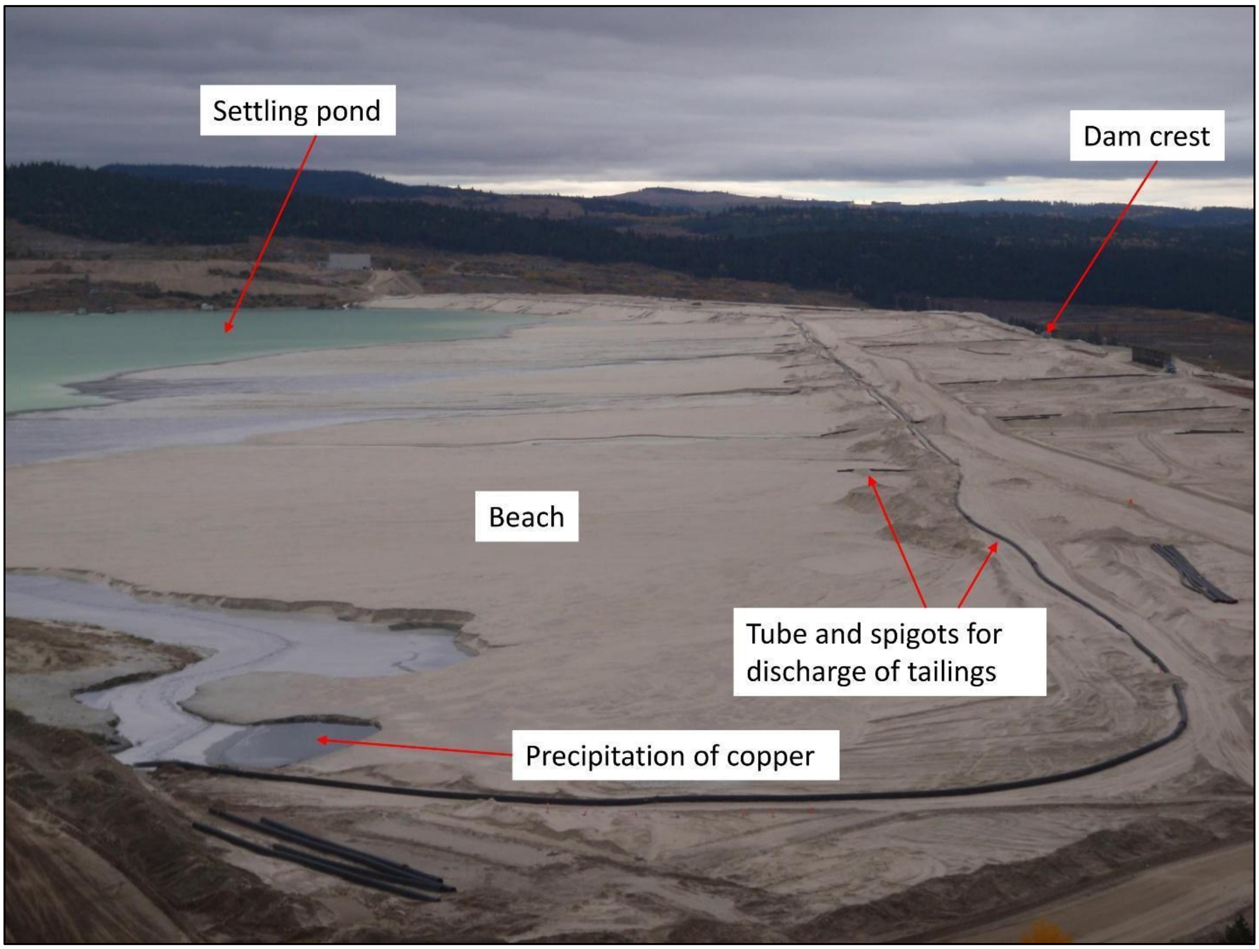


Figure 11. In conventional tailings management, tailings and water from the ore processing plant are injected in the upstream direction from spigots along the dam crest. The coarser tailings settle closer to the dam crest to form a beach. The finer tailings and water travel farther upstream where the fine tailings settle out of suspension in the settling pond. Since there is no compaction of the tailings, they are susceptible to failure by liquefaction. An adequate beach width is crucial to keep the water table low within the tailings dam. The photo is a tailings dam at the Highland Valley Copper mine in British Columbia, Canada. The beach at this tailings storage facility is too narrow probably due to a lack of coarse tailings coming from the ore processing plant. Photo by the author taken on September 27, 2018.

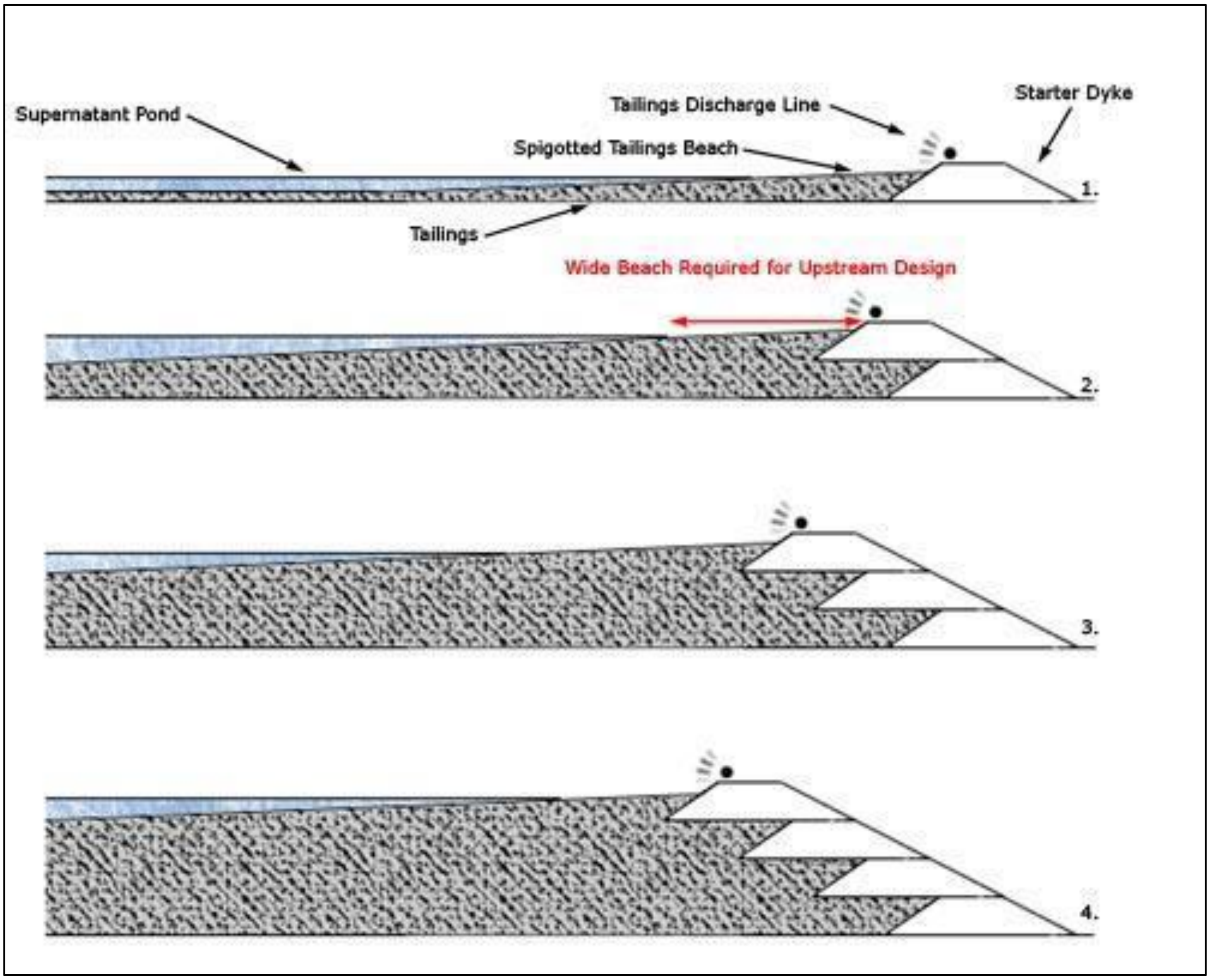


Figure 12a. In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. Dikes can be constructed with mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (typically with proper compaction). The advantage of the method is its low cost because very little material is required for the construction of the dam. The disadvantage is that the dam is susceptible to failure due to seismic or static liquefaction because the non-compacted wet tailings are below the dam. For this reason, the upstream construction method is illegal in Brazil, Chile, Ecuador and Peru. Under any circumstances, an adequate beach width is necessary to maintain a sufficiently low water table beneath the dam. Figure from TailPro Consulting (2022).

METHODS OF TAILINGS DAM CONSTRUCTION

This review of the methods of tailings dam construction largely follows the textbook Planning, Design, and Analysis of Tailings Dams (Vick, 1990). Tailings can be divided into two sizes with very different physical properties, which are the coarse tailings or sands (larger than 0.075 mm) and the fine tailings or slimes (smaller than 0.075 mm). In conventional tailings management, the wet tailings are piped to the tailings storage facility with no dewatering, so that water contents are in the range 150-400%, where the water content is the ratio of the mass of water to the mass of dry solid particles. The mixture of tailings and water is then discharged into the tailings pond from the crest of the dam through spigots that connect to a pipe that comes from the ore processing plant (see Fig. 11). The discharge results in the separation of the sizes of tailings by gravity. The larger sands settle closer to the dam to form a beach. The smaller slimes and water travel farther from the dam to form a settling pond where the slimes slowly settle out of suspension. Typically, water is reclaimed from the settling pond and pumped back into the mining operation. It should be noted that the beach is essential for maintaining a low water table within the dam.

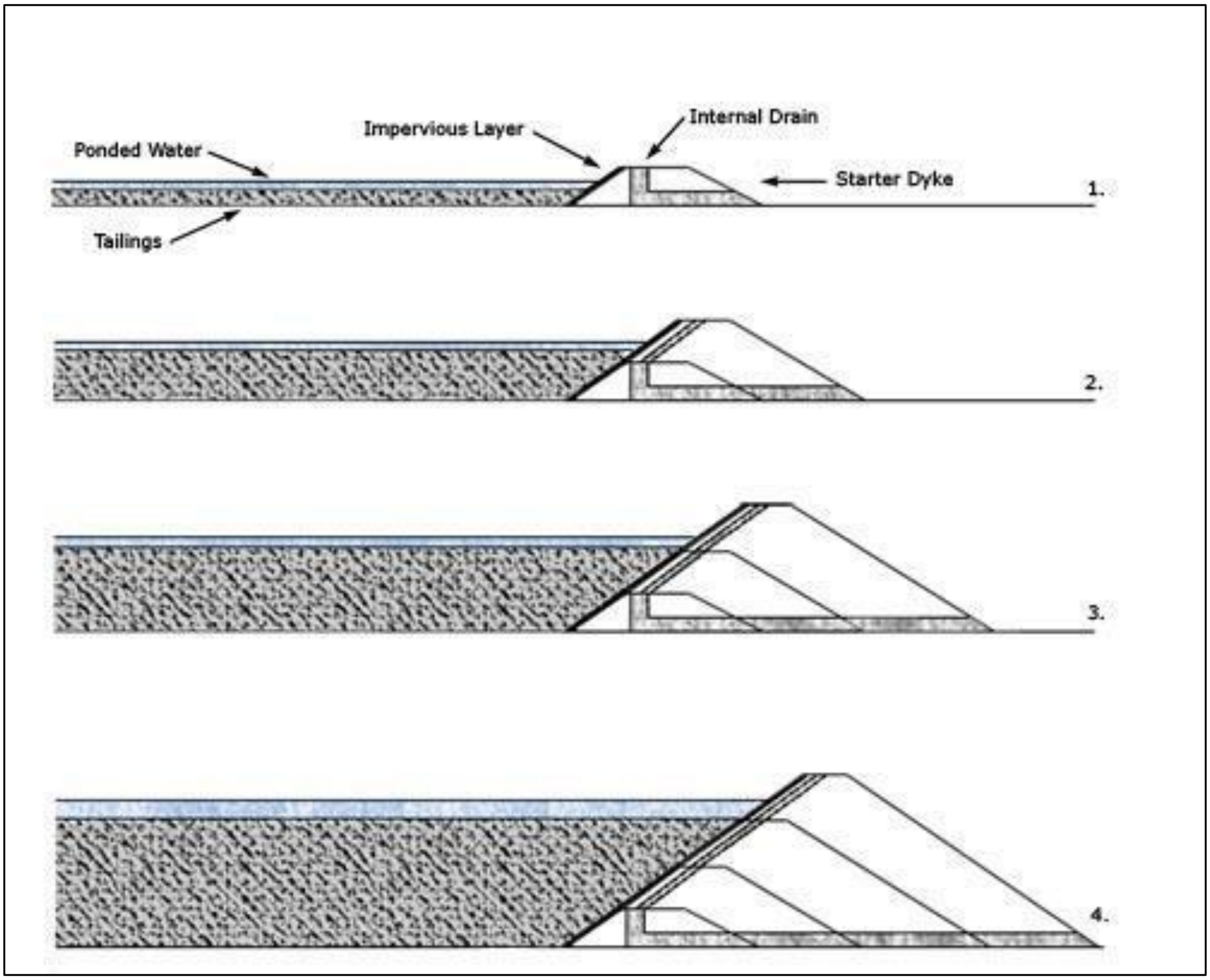


Figure 12b. In the downstream construction method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. Dikes can be constructed from mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (typically with proper compaction). The resistance to seismic and static liquefaction is high because there are no uncompacted tailings below the dam. The disadvantage of the method is its high cost due to the amount of material required to build the dikes (compare the dike volumes in Figs. 12a and 12b). Figure from TailPro Consulting (2022).

Each of the three common methods of building tailings dams (upstream, downstream and centerline) begins with a starter dike, which is constructed from natural soil, rockfill, mine waste rock or the tailings from an earlier episode of ore processing (see Figs. 12a). In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. It is most common to build successive dikes from waste rock or the coarser fraction of tailings (typically with appropriate compaction). The advantage of the method is its low cost since very little material is required for the construction of the dam (see Fig. 12a). The downstream construction method is the most expensive since it requires the most construction material (compare Figs. 12a and 12b). In this method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. The centerline construction method is a balance between the advantages and disadvantages of the downstream and upstream construction methods (compare Figs. 12a-c). In this method, successive dikes are constructed by placing construction material on the beach and on the slope downstream of the previous dike. The center lines of the raises coincide as the dam is built upwards (see Fig. 12c).

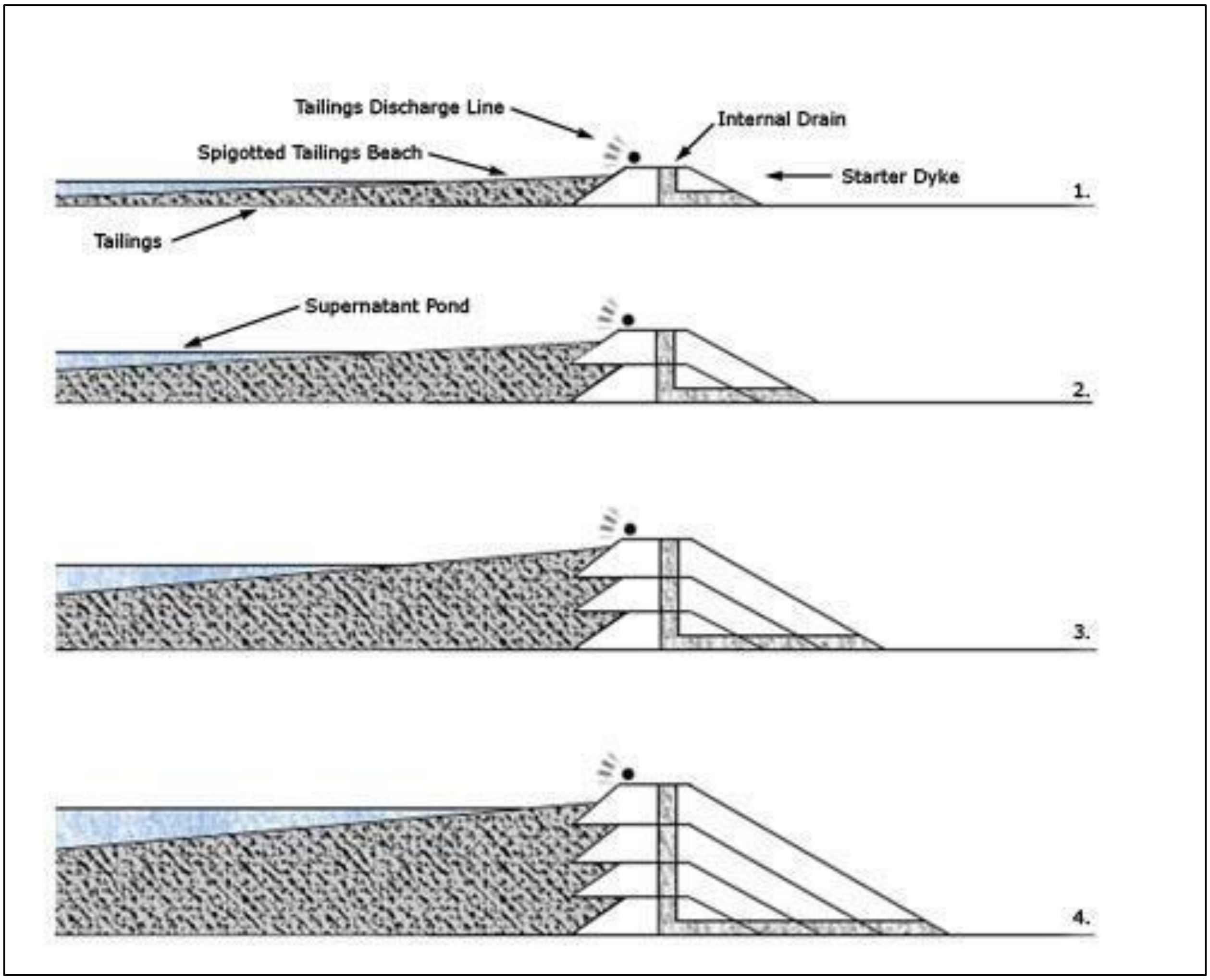


Figure 12c. In the centerline construction method, successive dikes are constructed by placing construction material on the beach and on the slope downstream of the previous dike. The central lines of the rises coincide as the dam is built upwards. Dikes can be constructed from mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (typically with proper compaction). The centerline method is intermediate between the upstream and downstream methods (see Figs. 12a-b) in terms of cost and risk of failure. The resistance to seismic and static liquefaction is moderate because there are still some uncompacted tailings below the dikes. It is still necessary to maintain a suitable beach to maintain a sufficiently low water table within the dam. Figure from TailPro Consulting (2022).

The common methods of tailings dam construction can be analyzed in terms of their vulnerability to the common causes of tailings dam failures. It will not be surprising that the less expensive construction methods are also more vulnerable to failure. Tailings dams constructed using the upstream method are especially vulnerable to failure by either seismic liquefaction or static liquefaction because the dam is built on top of the uncompacted tailings (see Fig. 12a). Thus, even if the dam temporarily maintains its structural integrity while the underlying tailings liquefy, the dam could fail by either falling into or sliding over the liquefied tailings. Dams constructed using the centerline method retain some vulnerability to failure during liquefaction because there are still some uncompacted tailings underneath the dikes (see Fig. 12c). On the other hand, a tailings dam constructed using the downstream method could survive the complete liquefaction of the tailings stored behind the dam (see Fig. 12b). Of course, proper design and construction are still needed to prevent liquefaction of the dam itself even when the downstream method is used.

From another perspective, an upstream dam is constructed on top of an unknown foundation (see Fig. 12a; Fuller, 2019). An accurate knowledge of the foundation is an essential feature of dam safety since both tailings dams and water-retention dams have failed due to yielding or settling of the foundation. The geotechnical properties of the tailings underlying the dikes can be predicted, but they are not actually known until they can be measured after dikes have been constructed on top of them. In the same way, the future evolution of the tailings (for example, due to compaction by the overlying dikes or drying of the tailings) can be predicted, but is not actually known until the future has occurred. This feature of upstream dams sets them apart from any other type of dam in which the geotechnical properties of the foundation can and should be a known quantity before the dam is constructed. Further aspects of the risk posed by the upstream construction method will be addressed in the Discussion section.

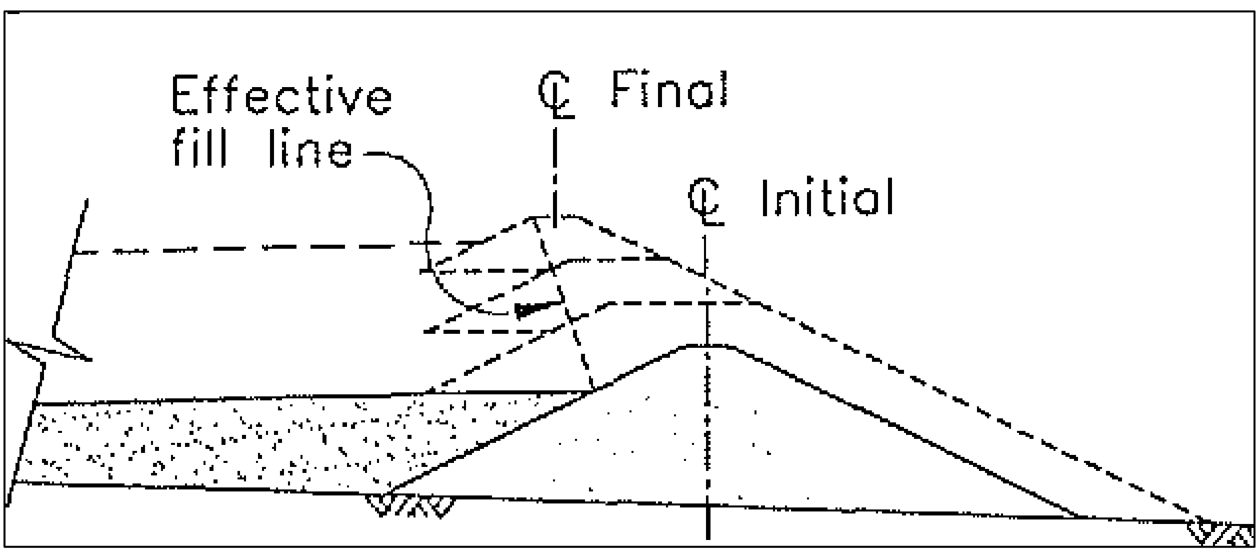


Figure 13. In the modified centerline construction method, the contact between the successive dikes and the uncompacted tailings slopes in an upstream direction (compare with Figs. 12a and 12c). According to TailPro Consulting (2022), "In countries where upstream construction is not permitted (i.e. due to seismic risk), the modified centreline method may also not be permitted due to the concept of partially placing construction material on the existing tailings beach." Safety First: Guidelines for Responsible Mine Tailings Management confirms that "since modified centerline construction still involves constructing a portion of the dam on top of the uncompacted tailings, it must be considered a variant of upstream construction, similarly subject to the cautions and restrictions associated with upstream-type dams presented in this document" and adds that "in some jurisdictions where upstream dams have already been banned, operating companies have used the concept of 'modified centerline' to avoid the prohibition. What these operating companies call a modified centerline design must be considered an upstream dam because it still includes construction of the dam on top of uncompacted tailings. Operating companies must correctly identify upstream construction to regulatory agencies" (Morrill et al., 2022). Figure from Haile and Brouwer (1994).

Just as the centerline method was developed as a compromise between the upstream and downstream methods, the modified centerline method was developed as a compromise between the upstream and centerline methods (see Fig. 13; Haile and Brouwer, 1994). According to Haile and Brouwer (1994), who were advocating for the adoption of the modified centerline method, "The modified centreline cross-section is similar to a centreline cross-section but with the contact between the embankment fill and the tailings sloping slightly upstream" (see Fig. 13). The modified centerline method re-introduces the placement of construction material (such as the coarser fraction of tailings with appropriate compaction) on top of uncompacted tailings, only to a lesser degree than in the upstream method (compare Fig. 12a with Fig. 13). Since the modified centerline method retains the essential feature that makes the upstream method vulnerable to failure by seismic or static liquefaction (placement of dam construction material on top of uncompacted tailings), a more appropriate name for the same construction type would have been the "modified upstream" method. In fact, ICOLD (2021) essentially repeats the diagram from Haile and Brouwer (1994) (see Fig. 13), but labels it the "modified upstream" method (see Fig. 14). This logic was also followed in Safety First: Guidelines for Responsible Mine Tailings Management, which stated, "Since modified centerline construction still involves constructing a portion of the dam on top of the uncompacted tailings, it must be considered a variant of upstream construction, similarly subject to the cautions and restrictions associated with upstream-type dams presented in this document" (Morrill et al., 2022). Morrill et al. (2022) continue, "In some jurisdictions where upstream dams have already been banned, operating companies have used the concept of 'modified centerline' to avoid the prohibition. What these operating companies call a modified centerline design must be considered an upstream dam because it still includes construction of the dam on top of uncompacted tailings. Operating companies must correctly identify upstream construction to regulatory agencies." TailPro Consulting (2022) also cautions, "In countries where upstream construction is not permitted (i.e. due to seismic risk), the modified centreline method may also not be permitted due to the concept of partially placing construction material on the existing tailings beach."

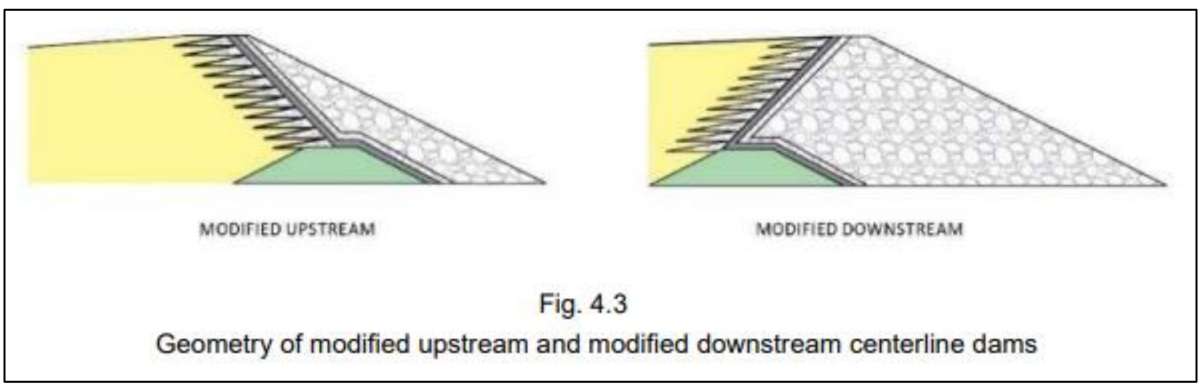


Figure 14. The above diagram from ICOLD (2021) confirms that what has been called the "modified centerline" method (see Fig. 13) should be referred to as the "modified upstream" method. The so-called "modified centerline" method retains the essential characteristics of the upstream method in that successive dikes are constructed on top of uncompacted tailings (compare with Fig. 12a). Figure from ICOLD (2021).

Tailings dams that combine upstream, downstream and/or centerline raises are referred to as "hybrid" dams in the Global Tailings Portal (Franks et al., 2021; GRID-Arendal, 2022). However, the presence of a single upstream raise should place a tailings dam in the category of "upstream" dams. A single upstream raise places dam construction material on top of uncompacted tailings and this fact is not altered by other raises that use the centerline or downstream method. For example, at the Riotinto mine in Spain, the construction of a rock wall using the downstream method on top of an upstream dam increased the probability of liquefaction by increasing the load on both the underlying dam and the underlying tailings (Emerman, 2019). According to Morrill et al. (2022), "A downstream or centerline raise constructed on top of an existing upstream dam or on top of uncompacted tailings still constitutes an upstream dam."

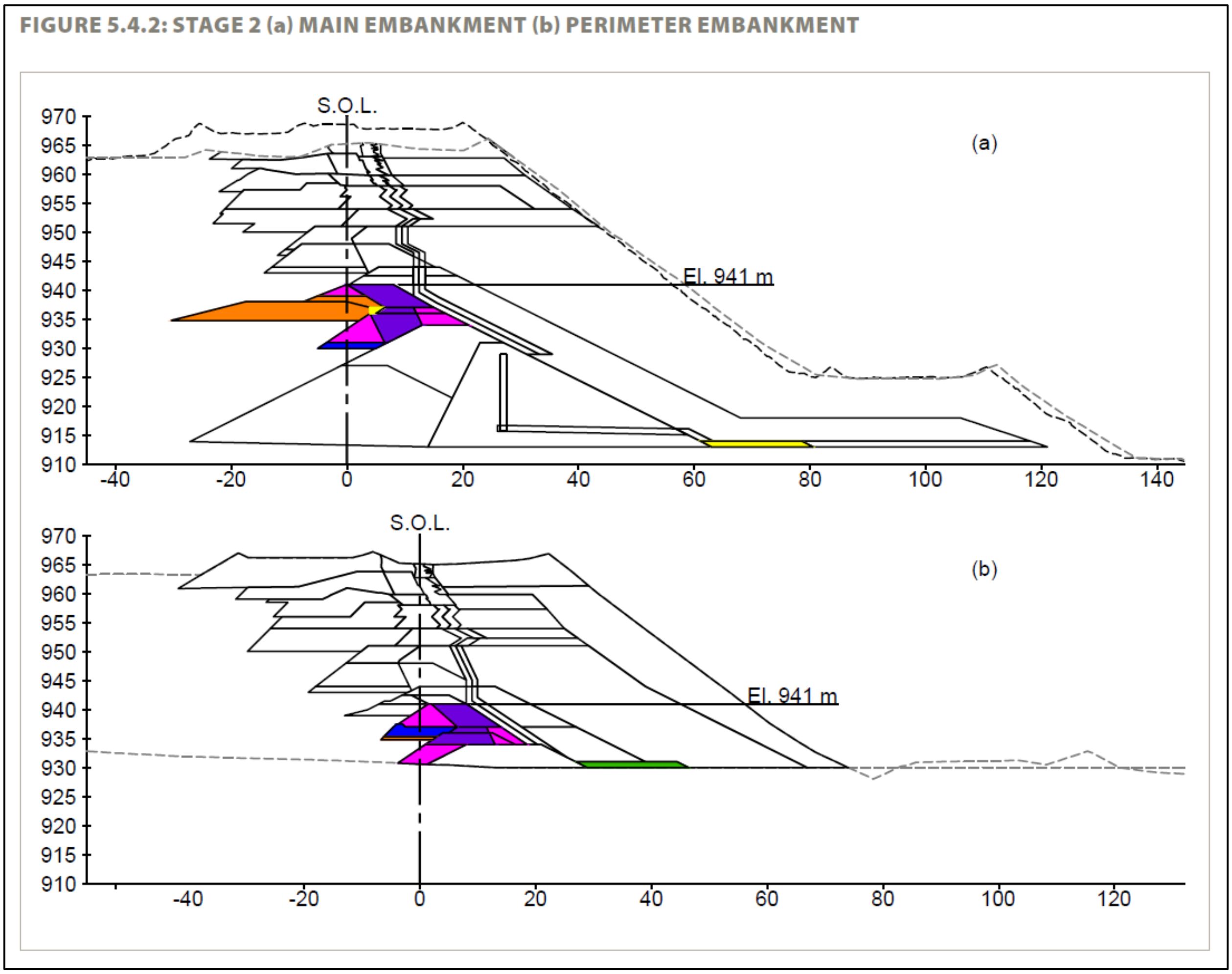


Figure 15a. Although the tailings dam at the Mount Polley mine was designed and permitted as a centerline dam, the Stage 2 dam raise (shown in colors) was constructed using the upstream method. According to Independent Expert Engineering Investigation and Review Panel (2015a), "The as-built configuration of the Stage 2 Main Embankment shown in Figure 5.4.2(a) differed from the design in several important respects … Rather than adhering to a 'centreline' configuration, raise 2 utilized entirely 'upstream' construction. The same conditions prevailed for the Perimeter Embankment shown in Figure 5.4.2(b). These as-built conditions were never reconciled with the Stage 2 stability analyses, which had been predicated on the original design configuration." Although one source (Center for Science in Public Participation (2022)) describes the Mount Polley tailings dam as a modified centerline dam, this is non-standard terminology. The presence of dikes (such as the Stage 2 dam raise) on top of uncompacted tailings should classify the Mount Polley tailings dam as an upstream dam (compare with Figs. 12a, 12c and 14). According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam or on top of uncompacted tailings still constitutes an upstream dam" (Morrill et al., 2022). Figure from Independent Expert Engineering Investigation and Review Panel (2015a).

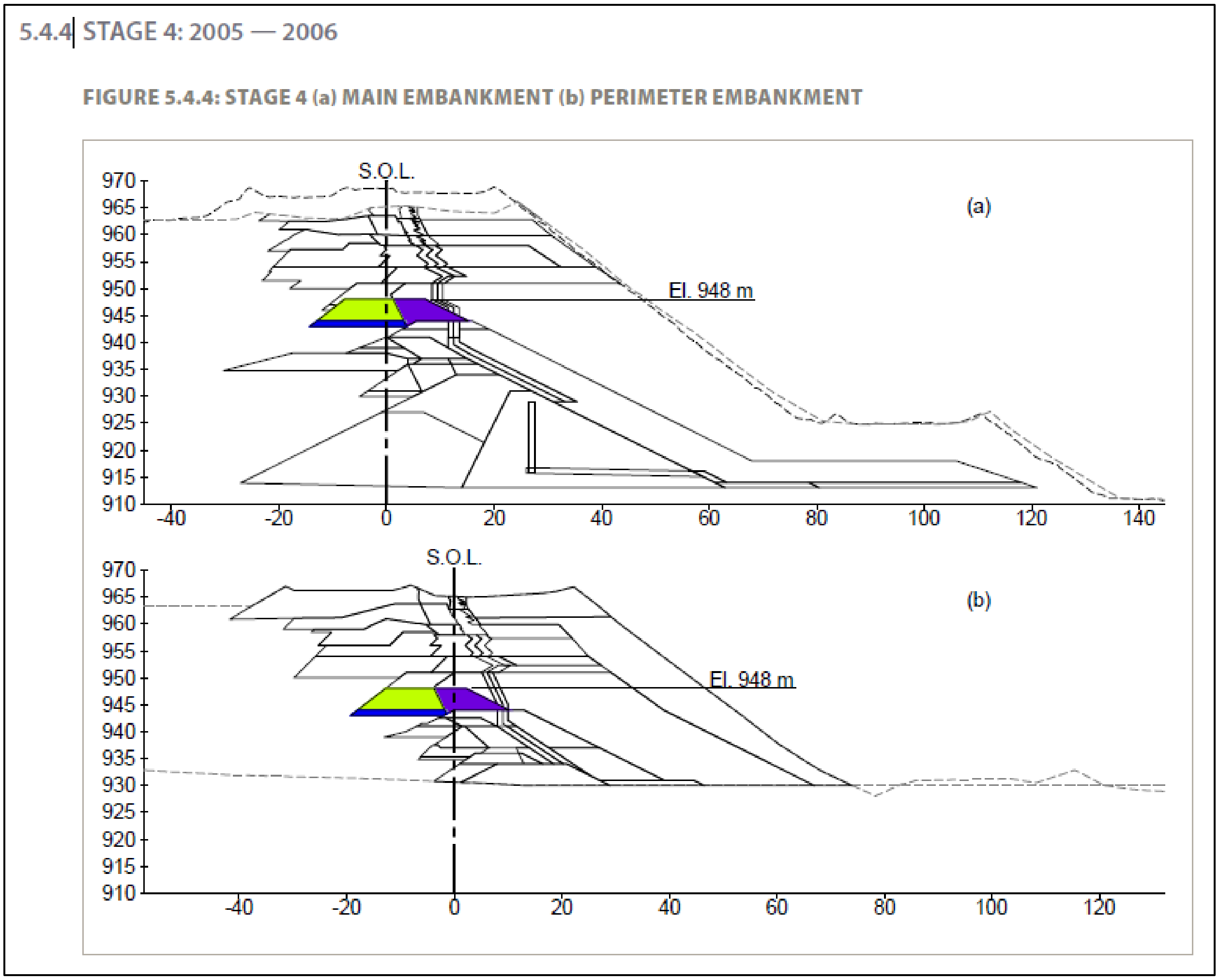


Figure 15b. Although the tailings dam at the Mount Polley mine was designed and permitted as a centerline dam, the Stage 4 dam raise (shown in colors) was constructed using the upstream method. According to Independent Expert Engineering Investigation and Review Panel (2015a), "As illustrated in Figure 5.4.4, only the cap was constructed in Stage 4 without any additional rockfill on the downstream slope, resulting in another 'upstream'-type raise." Although one source (Center for Science in Public Participation (2022)) describes the Mount Polley tailings dam as a modified centerline dam, this is non-standard terminology. The presence of dikes (such as the Stage 4 dam raise) on top of uncompacted tailings should classify the Mount Polley tailings dam as an upstream dam (compare with Figs. 12a, 12c and 14). According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam or on top of uncompacted tailings still constitutes an upstream dam" (Morrill et al., 2022). Figure from Independent Expert Engineering Investigation and Review Panel (2015a).

For this report, a particularly relevant example of a hybrid dam that should be regarded as an upstream dam is the tailings dam at the Mount Polley mine in British Columbia, which failed in August 2014 with a release of 24 million cubic meters of tailings. The permit for the tailings dam called for the use of the centerline method. However, the Stage 2 and Stage 4 raises for the tailings dam used the upstream method, placing the new dam construction material directly on top of the uncompacted tailings, in violation of the permit (see Figs. 15a-b). According to Independent Expert Engineering Investigation and Review Panel (2015a), "The as-built configuration of the Stage 2 Main Embankment shown in Figure 5.4.2(a) differed from the design in several important respects … Rather than adhering to a 'centreline' configuration, raise

2 utilized entirely 'upstream' construction. The same conditions prevailed for the Perimeter Embankment shown in Figure 5.4.2(b). These as-built conditions were never reconciled with the Stage 2 stability analyses, which had been predicated on the original design configuration … As illustrated in Figure 5.4.4, only the cap was constructed in Stage 4 without any additional rockfill on the downstream slope, resulting in another 'upstream'-type raise." The motivation for the change from centerline to upstream construction was a lack of sufficient waste rock for dam construction, which also motivated the steepening of the dam embankment. According to Independent Expert Engineering Investigation and Review Panel (2015a), "But since the material would now be sourced from mine waste rather than quarried, mine production and delivery had to be accommodated. Due to related restrictions, it was planned to place the Zone C outslope to an 'interim' 1.4H:1V inclination—rather than the design basis 2.0H:1V—as a temporary expedient until mine waste delivery could catch up with construction. The steeper slope would be expanded and flattened to 2.0H:1V 'once the embankments have reached the Stage 5 design elevation' … Stage 5 construction proceeded from Stage 4 in a continuous, uninterrupted campaign and was completed in November 2007. But instead of rectifying the interim steep slopes at this time as had been intended, such measures were left to future stages of embankment raising."

SUMMARY OF TAILINGS DAMS AT COPPER MOUNTAIN MINE

The tailings dams at the Copper Mountain are raised by pumping the wet tailings from the ore processing plant to cyclones that are set along the dam crest. The cyclones separate the tailings by size. The coarser sands are discharged through the underflow of the cyclones to construct the dams without any compaction of the sands (see Fig. 16). The finer sands, slimes, and water are discharged through the overflow of the cyclones (see Figs. 17a-b). The finer sands settle closer to the dam crest to form tailings beaches, while the slimes and water are carried to the interior of the tailings management facility (see Figs. 2 and 17a-b, compare with Fig. 11).

It is important to note that there is no compaction of the material used to construct the tailings dams. The use of uncompacted, cycloned sand is still used for some tailings dams, but it is becoming increasingly less common. Even in 1990, Vick (1990) wrote, "Compaction of cycloned sand is a significant issue in embankment design, and, as explained above, the various cycloning methods vary in their ability to accommodate compaction procedures. Compaction of embankment sands is often desirable to reduce pore pressure buildup during shear and the possibility of flow slides … But compaction becomes of critical design importance in determining the susceptibility of saturated embankment sands to seismic liquefaction." The SME (Society for Mining, Metallurgy and Exploration) Tailings Management Handbook – A Life-Cycle Approach discusses the means for achieving adequate compaction of cycloned tailings sands. According to Davies et al. (2022), "Often, the cycloned sand is re-slurried to a lower water content to facilitate conventional pumping and distribution if the sand is being used for embankment construction. If deposited in managed cells, it can be compacted to provide a very stable containment material, even in extreme environments (high seismicity and rainfall)."

Photo 16: Cyclone discharging underflow (cyclone sand) on downstream face of West Dam

Figure 16. The tailings dams at the Copper Mountain mine are raised by using cyclones to separate the tailings by size. The coarser tailings (sands) are discharged through the underflow to construct the dam. The coarser tailings that form the dam are not compacted. Photo from Tetra Tech (2022).

The starter dikes for the East and West Dams were constructed in 1971 with the first dam raises in 1973. The initial construction method was centerline. The construction method changed to upstream in 1980 until the temporary closure of the tailings management facility in 1996. The reactivation of the tailings facility in 2011 involved a further combination of centerline and upstream raises. According to the 2016 Dam Safety Review, "Since reactivation of the TMF [Tailings Management Facility], the West Dam has been raised using the centerline construction method, whereas the East Dam has been raised using a centreline construction method, but on a modified centreline" (Klohn Crippen Berger, 2017a). According to the 2021 Dam Safety Review, "On reactivation in 2011, the dam raising method shifted back to a primarily centerline construction; however, the East Dam construction plan allowed for initial upstream raises" (Tetra Tech, 2022). Based on the preceding section, both the East and West Dams should be regarded as upstream dams. In fact, the various generalized cross-sections of the East and West Dams confirm that the dams consist primarily of uncompacted cycloned sands placed on top of uncompacted fine-grained tailings (e.g., Klohn Crippen Berger, 2022a; see Fig. 18). In the 2022 British Columbia Existing and Future Tailings Storage Database, the Copper Mountain mine is listed as a mine site with upstream tailings dams, as is the Mount Polley mine. Further aspects of the tailings dams at the Copper Mountain mine will be discussed in the Results section.

Photo II-29 West Dam beach looking east from the dam crest (July 2, 2020)

Figure 17a. The overflow from the cyclones (see Fig. 16) consisting of finer tailings and water is discharged from the crest of the West Dam toward the interior of the tailings management facility. The coarser fraction of the overflow settles closer to the dam crest to form a tailings beach (foreground of photo; compare with Figs. 2 and 11). The finest fraction of the overflow (slimes) is carried to the interior of the tailings management facility (background of photo; compare with Figs. 2 and 11). Photo from Tetra Tech (2022).

METHODOLOGY

The objective of this report was addressed by comparing the characteristics of the various Levels of Engineering (see Tables 1a-e) with information available in annual Dam Safety Inspections from 2014 through 2022 (AMEC, 2014, 2016a; Klohn Crippen Berger, 2017b, 2018, 2019, 2021, 2022a), five-year Dam Safety Reviews for 2016 and 2021 (Klohn Crippen Berger, 2017a; Tetra Tech, 2022), and various reports written in support of the proposed expansion (Copper Mountain Corporation, 2020; Klohn Crippen Berger, 2022b). Due to the pandemic, there was no dam safety inspection in 2020. For some important documents that were not available to the author, including calculations of the factor of safety (Bechtel, 1971; Klohn, 1989; AMEC, 2011, 2015, 2016b-c; Klohn Crippen Berger, 2020a-b), the author relied on summaries in Tetra Tech (2022). The author did not personally visit the Copper Mountain mine site.

By far, the most useful document was the 2021 Dam Safety Review (Tetra Tech, 2022). It is important to consider the distinction between an annual Dam Safety Inspection and a five-year Dam Safety Review. In general terms, a Dam Safety Inspection is primarily a visual inspection with a review of the dam instrumentation records. By and large, a Dam Safety Inspection takes into consideration only the construction and the changes that have occurred since the previous inspection. By contrast, a five-year Dam Safety Review should be more comprehensive and should consider the entire history of the dam. According to mining regulations in British Columbia, “The purpose of a … Dam Safety Inspection is to review and evaluate the adequacy of performance and operation of the overall facility, with specific attention on short-term physical condition and surveillance results … The purpose of the DSR [Dam Safety Review] is to review and evaluate the performance and operation of the facility relative to dam safety standard of practice” (Ministry of Energy and Mines (British Columbia), 2016).

Photo II-2 East Dam beach and pond looking north from the Tailings Road (September 11, 2020)

Figure 17b. The overflow from the cyclones (see Fig. 16) consisting of finer tailings and water is discharged from the crest of the East Dam toward the interior of the tailings management facility. The coarser fraction of the overflow settles closer to the dam crest to form a tailings beach (middle to right-hand side of photo; compare with Figs. 2 and 11). The finest fraction of the overflow (slimes) is carried to the interior of the tailings management facility (left-hand side of photo; compare with Figs. 2 and 11). Photo from Tetra Tech (2022).

The guidelines of the Canadian Dam Association (2013, 2019) emphasize the comprehensive nature of the Dam Safety Review. According to Canadian Dam Association (2013), “The Dam Safety Review is a systematic review and evaluation of all aspects of design, construction, operation, maintenance, processes, and other systems affecting a dam’s safety, including the dam safety management system. The review defines and encompasses all components of the ‘dam system’ under evaluation (dams, spillways, foundations, abutments, reservoir, tailraces [the water channels below the dam], etc.). The review should be based on current knowledge and methods, which may be different from the acceptable practices at the time of original construction or a prior Dam Safety Review. The level of detail in the Dam Safety Review should be sufficient either to demonstrate that the dam meets dam safety requirements or to identify areas where conformance cannot be demonstrated and future investigation or action is needed. The level of detail may be modified on the basis of previous assessments, complexity of the dam, continuity of surveillance and records, external and internal hazards, operating history, dam performance and age, and the need for public protection during operation.” Recent investigations into dam failures have also underlined the need for comprehensive reviews of the entire history of a dam. With regard to the failures of the Edenville and Sanford dams in Michigan, Independent Forensic Team (2022) wrote, "Repeating a lesson to be learned from the Oroville Dam spillway incident forensic investigation (France et al. 2018), physical inspections, while a necessary part of a dam safety program, are not sufficient by themselves to identify risks and manage safety. Dam safety evaluations need to include periodic comprehensive reviews of original design and construction, performance, operations, analyses of record, maintenance, and repairs."

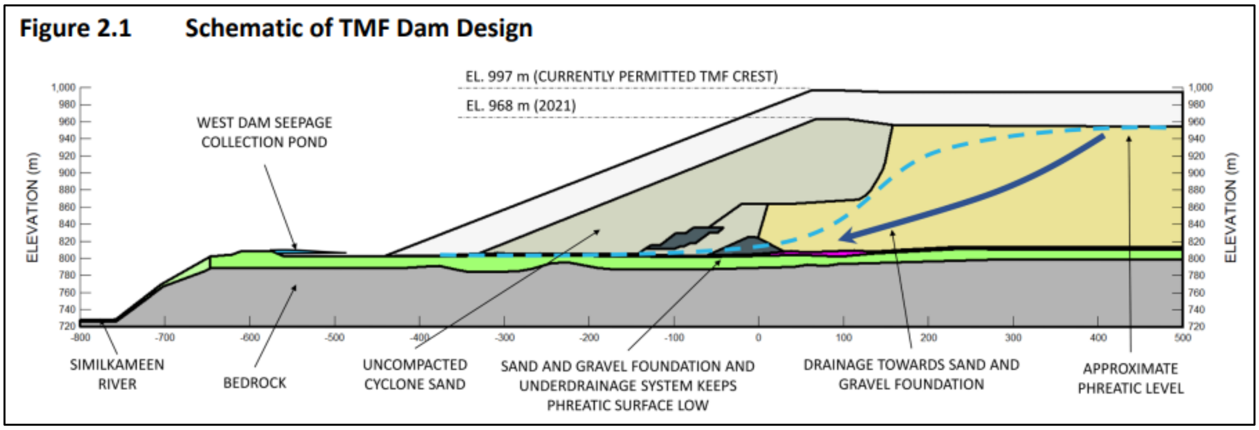


Figure 18. The cross-section of the West Dam clarifies that, despite the use of the term "modified centerline," the tailings dams at the Copper Mountain mine are constructed using the upstream method, in that the dikes (uncompacted cycloned sand) are constructed on top of the uncompacted, fine-grained tailings (tan color) that they are impounding (compare with Figs. 12a, 13 and 14). The upstream construction method is the cheapest because it requires the least amount of construction material (compare Figs. 12a-c). The method is also the most dangerous because, if the underlying tailings liquefy, the dikes can fail by falling into or sliding over the liquefied tailings even if the dikes temporarily maintain their structural integrity. The upstream construction method is prohibited in Brazil, Chile, Ecuador and Peru. Figure from Klohn Crippen Berger (2022a).

Based on the information in the available documents, each of the characteristics for Level of Engineering in the checklists created by Silva et al. (see Tables 1a-e) was assessed for the tailings dams at the Copper Mountain mine. Each of the characteristics was assessed with three options, which were "not fulfilled" (indicated with red), "partially fulfilled or unknown" (indicated with yellow), and "fulfilled" (indicated with green) (see Tables 1a-e). Based on the distribution of colors, for each area of the Level of Engineering, a holistic judgment was made in terms of assigning the tailings dams at the Copper Mountain mine to the categories Best, Above Average, Average, Poor, or to a category midway between the preceding categories, such as Average to Above Average. For the assessment of the Level of Engineering, no distinction was made between the East Dam and the West Dam. A common theme throughout the assessments was that the Level of Engineering was far superior for the construction that began in 2015 as opposed to the pre-2015 construction. Since, according to Klohn Crippen Berger (2022b), the approximate heights of the East Dam and West Dam at the end of 2014 were 129.5 meters and 121.5 meters, respectively (75% and 74% of the present height), due consideration was given to the low quality of the earlier construction in the assignment of the tailings dams at the Copper Mountain mine to the appropriate Level of Engineering in this report.

In most cases, characteristics that were fulfilled beginning in 2015 and not fulfilled in the pre-2015 period were assessed as "partially fulfilled."

For each tailings dam, the various consulting reports include multiple possible values of the static factor of safety, based upon different cross-sections of the dam and different assumed and measured input parameters. The relevant factors of safety were considered to those that were predicted to exist once the permitted elevation has been reached in 2027. The entire range of calculated factors of safety at the permitted elevation was considered and the annual probability of failure was estimated for each dam and for each static factor of safety, using the overall Level of Engineering for the tailings management facility. For each dam, the best estimate for the annual probability of failure was calculated as the geometric mean of the range of annual probabilities of failure. The use of the geometric mean is consistent with the logarithmic axis for annual probability of failure (see Fig. 10) and the way in which Silva et al. (2008) interpolated between categories. Since the Copper Mountain Tailings Management Facility would fail if either dam failed, the best estimate for the annual probability of failure of the tailings facility was calculated as the sum of the annual probabilities of failure of the East and West Dams. Further information about the methodology will be provided in the Results section.

RESULTS

Level of Engineering: Design – Investigation

The area Design – Investigation largely deals with the site investigation that should have occurred prior to the construction of the tailings management facility. It is particularly important to locate all weak layers, such as the clay units of glaciolacustrine (former glacial lake) beds, that might not be able to support the weight of a tailings management facility. The need for proper site characterization is particularly acute in British Columbia due to the predominance of glacial deposits and because the failure of the tailings dam at the Mount Polley mine resulted from the collapse of the dam into a glaciolacustrine bed. According to the Mount Polley expert review panel, "The Panel concluded that the dominant contribution to the failure resides in the design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous GLU [Glaciolacustrine Unit] layer in the vicinity of the breach and to recognize that it was susceptible to undrained failure when subject to the stresses associated with the embankment" (Independent Expert Engineering Investigation and Review Panel, 2015a).

A full location and characterization of possible weak layers in the foundation of the Copper Mountain Tailings Management Facility is critical because the current geologic models by Klohn Crippen Berger (2022a) identify a continuous lacustrine silt/clay unit and a discontinuous glaciolacustrine clay unit in the vicinity of the East Dam (see Fig. 19a), as well as a discontinuous lacustrine silt/clay unit in the vicinity of the West Dam (see Fig. 19b). The geologic models are a result of some boreholes that were drilled into the foundation, but only in the vicinities of the starter dikes for the East and West Dams and not farther upstream (toward the interior of the tailings management facility). According to the 2021 Dam Safety Review, "Investigations which penetrated into the foundation upstream of the Starter Dam are more limited, with only one or two boreholes which penetrate the foundation materials to a relatively limited depth (less than 10 m). Bechtel (1971) advanced several boreholes in the foundation material prior to the start of mining upstream of the Starter Dams, but it is unclear if these are incorporated into the geologic model used for design" (Tetra Tech, 2022). Tetra Tech (2022) concluded, “There is limited foundation information upstream of the Starter Dam at both dams.” Tetra Tech (2022) further emphasized that the characterization of possible weak layers was especially incomplete for the West Dam. According to Tetra Tech (2022), “Glaciolacustrine clay was identified in only one borehole (BH12-02E) at the East Dam (KCB 2020c) [Klohn Crippen Berger (2022a) in this report]. This material was not identified at the West Dam. However, boreholes upstream of the Starter Dam at the West Dam do not penetrate to bedrock, so the GLU may have been missed.”

Table 7-1: East Dam Geologic Model (after KCB 2020c)

Geologic Unit	Thickness (m)	Approximate Elevation Range (m)
Lacustrine Silt/Clay	0.2 to 6.9 (continuous)	794 – 808
Fluvial Sand & Gravel	0.5 to 14 (discontinuous)	785 – 810
Glaciofluvial Sand & Gravel	4 to 53 (continuous)	< 750 – 805
Glaciolacustrine Clay	0.5 to 5 (discontinuous)	780 – 790
Glacial Till	0.5 to 5 (discontinuous or interbedded)	785 – 805
Volcanic Bedrock	N/A	Upper surface varies between <750 – 785

Figure 19a. The category Best for Level of Engineering in the area of Design - Investigation requires the engineering team to “determine site geologic history” and to “locate all nonuniformities (soft, wet, loose, high, or low permeability zones)” (see Table 1a). The table above indicates that this was done to some extent in the vicinity of the East Dam. However, Tetra Tech (2022) has critiqued the lack of knowledge of the foundation of the tailings dam, which is difficult to remedy at the present time. According to Tetra Tech (2022), “Investigations which penetrated into the foundation upstream of the Starter Dam are more limited, with only one or two boreholes which penetrate the foundation materials to a relatively limited depth (less than 10 m). Bechtel (1971) advanced several boreholes in the foundation material prior to the start of mining upstream of the Starter Dams, but it is unclear if these are incorporated into the geologic model used for design. Additional foundation investigation upstream of the Starter Dam would be of benefit to improving the understanding of the foundation in these locations where relatively little recent information is available, particularly at the East Dam, where the GLU [glaciolacustrine unit] is present. However, given the height of the dam and the presence of a thick layer [of] the dense fluvial sand and gravel overlying this material, penetrating to and through the foundation may prove prohibitively difficult.” Based on the relative lack of knowledge of the geologic history and the locations of nonuniformities, as well as the lack of evaluation of the design and performance of nearby structures, the lack of analysis of historic aerial photographs, and the relative lack of field measurements of pore pressure (see Fig. 32), the category for Level of Engineering in the area of Design – Investigation was chosen as Above Average (see Table 1a). KCB (2020c) in the table above is Klohn Crippen Berger (2022a) in this report. Table from Tetra Tech (2022).

Based on the above, at the present time, it is essentially unknown as to whether the foundation beneath the West Dam or the interior of the tailings management facility could support the weight of additional tailings. Unfortunately, it is either very difficult or impossible to obtain this knowledge once the tailings management facility has been constructed to such great heights. According to the 2021 Dam Safety Review, “Additional foundation investigation upstream of the Starter Dam would be of benefit to improving the understanding of the foundation in these locations where relatively little recent information is available, particularly at the East Dam, where the GLU [glaciolacustrine unit] is present. However, given the height of the dam and the presence of a thick layer [of] the dense fluvial sand and gravel overlying this material, penetrating to and through the foundation may prove prohibitively difficult.”

Table 7-2: West Dam Geologic Model (after KCB 2020c)		
Geologic Unit	**Thickness (m)**	**Approximate Elevation Range (m)**
Lacustrine Silt & Clay	0.8 to 1.5 (discontinuous)	801 – 806
Glaciofluvial Sand & Gravel	10 to 20 (continuous)	780 – 808
Fluvial Sand & Gravel	0.5 to 14 (discontinuous)	795 – 805
Glacial Till	0.5 to 1.5 (interbedded)	790 – 794
Volcanic Bedrock	N/A	Upper surface varies between 780 – 794

Figure 19b. The category Best for Level of Engineering in the area of Design - Investigation requires the engineering team to "determine site geologic history" and to "locate all nonuniformities (soft, wet, loose, high, or low permeability zones)" (see Table 1a). The table above indicates that this was done to some extent in the vicinity of the West Dam. However, Tetra Tech (2022) has critiqued the lack of knowledge of the foundation of the tailings dam, which is difficult to remedy at the present time. According to Tetra Tech (2022), "Investigations which penetrated into the foundation upstream of the Starter Dam are more limited, with only one or two boreholes which penetrate the foundation materials to a relatively limited depth (less than 10 m). Bechtel (1971) advanced several boreholes in the foundation material prior to the start of mining upstream of the Starter Dams, but it is unclear if these are incorporated into the geologic model used for design. Additional foundation investigation upstream of the Starter Dam would be of benefit to improving the understanding of the foundation in these locations where relatively little recent information is available, particularly at the East Dam, where the GLU [glaciolacustrine unit] is present. However, given the height of the dam and the presence of a thick layer [of] the dense fluvial sand and gravel overlying this material, penetrating to and through the foundation may prove prohibitively difficult." Based on the relative lack of knowledge of the geologic history and the locations of nonuniformities, as well as the lack of evaluation of the design and performance of nearby structures, the lack of analysis of historic aerial photographs, and the relative lack of field measurements of pore pressure (see Fig. 32), the category for Level of Engineering in the area of Design – Investigation was chosen as Above Average (see Table 1a). KCB (2020c) in the table above is Klohn Crippen Berger (2022a) in this report. Table from Tetra Tech (2022).

The area Design – Investigation also deals with the measurement of field pore pressures in the foundation prior to construction, as well as with the ongoing measurement of field pore pressures in the foundation, tailings deposit, and tailings dams during construction and operation. The 2021 Dam Safety Review drew attention to the lack of piezometers (instruments used to measure field pore pressure) and the resulting difficulty in determining the position of the water table for use in stability analyses. According to Tetra Tech (2022), "Given the relatively sparse data upstream of the dam crest, we do not consider the lower projections of Piezometric No. 2 and No. 3 – which are up to 250 m upstream of the most recently collected data – to be justified. While KCB (2020d) [Klohn Crippen Berger (2020b) in this report] notes that long term analyses should consider more conservative phreatic surfaces [positions of the water table], Tetra Tech suggests that, even for short term analyses, the lower phreatic surfaces upstream of the dam crest (through the tailings) represented by Piezometric No. 2 and No. 3, are not sufficiently supported by data in this area." For clarification, Piezometric No. 2 and No. 3 refer to particular assumptions regarding the position of the water table that were made by Klohn Crippen Berger (2020b) in their calculation of the factor of safety. A conservative phreatic surface refers to a reasonably high assumption for the position of the water table, which would minimize the value of the factor of safety.

The primary deficiency or non-conformance that was noted by the 2021 Dam Safety Review was "Limited piezometers upstream of Starter Dams" (Tetra Tech, 2022) with the recommended action to "Install VWPs [Vibrating Wire Piezometers] under crest at both the West and East Dam. The instruments should be targeted to intercept relevant units (foundation, tailings and lower cyclone sands)" (Tetra Tech, 2022). For both the East and West Dams, Tetra

Tech (2022) warned that "there are no functional piezometers at the dam crests." With regard to the West Dam, Tetra Tech (2022) wrote, "Tetra Tech considers replacement of crest piezometer critical to dam safety management, as the piezometric levels through the dam play a large role in the dam stability, and the closest currently functional piezometer to the crest of the dam is located approximately 75 m downstream of the crest centerline. Tetra Tech suggests that piezometers be installed in the cyclone sands, tailings and foundation at a second location on or near the dam crest … installation of piezometers in the foundation upstream of the Starter Dam is recommended to gather data on trends where no drainage blanket is present." With regard to the East Dam, Tetra Tech (2022) wrote, "Similar to the West Dam, there is a lack of operational piezometers on the crest of the East Dam. The closest operational piezometer is approximately 100 m downstream of the East Dam crest … installation of at [least] two new piezometers in the tailings is recommended … at least one additional piezometer in the foundation is recommended upstream of the Starter Dam." The significance of the lack of functional piezometers will be discussed further in the subsections Level of Engineering: Analyses and Documentation and Level of Engineering: Operation and Monitoring.

Based on the above information from the 2021 Dam Safety Review (Tetra Tech, 2022), the following characteristics for the Best Category in the area Design – Investigation were assessed as "partially fulfilled" (see Table 1a):

1) Locate all nonuniformities (soft, wet, loose, high, or low permeability zones)
2) Determine site geologic history
3) Determine subsoil profile using continuous sampling
4) Obtain undisturbed samples for lab testing of foundation soils
5) Determine field pore pressures

Since there is no indication of any evaluation of the design and performance of nearby structures, that characteristic is assessed as "unfulfilled" in the Best, Above Average and Average categories (see Table 1a). Since there is no indication of any analysis of historic aerial photographs, that characteristic is assessed as "unfulfilled" in the Best category (see Table 1a). The characteristic "Exploration program tailored to project conditions by qualified engineer" in the Above Average was fulfilled, since an exploration program was carried out prior to dam construction, but it was simply incomplete (which keeps the exploration program out of the Best category). The Average category would include "Estimate subsoil profile from existing data and borings," meaning that no new boreholes were drilled and no new data were collected specifically for a given project. The Average category would not be appropriate for the Copper Mountain Tailings Management Facility because new boreholes were drilled, although not enough boreholes, especially upstream of the starter dikes. Based on the above assessments, the Level of Engineering for Design – Investigation was assigned to the category Above Average with a score of 0.4 (see Table 1a).

Photo II-2 Test pit excavation on the West Dam crest (ND17-WD-01)

Figure 20a. The as-built reports by AMEC (2016a) and Klohn Crippen Berger (2017b, 2018, 2019) document extensive testing of construction material. However, as the above photo of a test pit indicates, this testing was carried out only on the material (uncompacted cycloned sand) that had been used to raise the tailings dams since the previous annual report. By contrast, there is essentially no documentation of any testing that occurred prior to 2015. Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current quality of testing and the pre-2015 testing, as well as the extensive construction that occurred prior to 2015, the category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Photo from Klohn Crippen Berger (2018).

Photo II-5 **Field Density Test Using Nuclear Densometer on the East Dam crest, inside excavated test pit, 1.2 m below the ground surface (ND17-ED-20)**

Figure 20b. Nuclear densometers are used to monitor the in-situ density of the uncompacted cycloned sands that are used to raise the tailings dams. The as-built reports by AMEC (2016a) and Klohn Crippen Berger (2017b, 2018, 2019) document extensive testing of construction material. However, as the above photo of a nuclear densometer in a test pit at a depth of 1.2 meters indicates, this testing has been carried out only on the material (uncompacted cycloned sand) that had been used to raise the tailings dams since the previous annual report. By contrast, there is essentially no documentation of any testing that occurred prior to 2015. Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current quality of testing and the pre-2015 testing, as well as the extensive construction that occurred prior to 2015, the category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Photo from Klohn Crippen Berger (2018).

Level of Engineering: Design – Testing

The as-built reports that are included with the Dam Safety Inspection reports for 2015 through 2018 (AMEC, 2016a; Klohn Crippen Berger, 2017, 2018, 2019) document the highest standards for the testing of material. As-built reports document the actual construction, which can differ from the design. Test pits were excavated into the deposits of cycloned sand (see Fig. 20a) and in-situ measurements included the measurement of density with the nuclear densometer (see Fig. 20b) and the measurement of saturated hydraulic conductivity with the Guelph permeameter (see Fig. 20c). Lab measurements were compared with field measurements resulting in, for example, excellent correlations between lab measurements of water content and field measurements with the nuclear densometer (see Fig. 21) and between lab measurements of the fines content and field measurements of the saturated hydraulic conductivity (see Fig. 22). Index properties of samples were measured for estimation of shear strength parameters (see Fig. 23a), as well as lab measurements of shear strength parameters under simulated field conditions (see Fig. 23b). According to Klohn Crippen Berger (2019), "The four triaxial specimens were prepared by the method of moist tamping at a moisture content of approximately 3% to a target initial dry density of about 1,500 kg/m^3 to simulate the mean minus one standard deviation of the average July 2018 field density testing data (KCB 2018). The prepared specimens were then saturated, consolidated (to simulate the expected consolidation pressure of the current shell below the ultimate dam), and sheared in undrained triaxial compression."

Photo II-9 Guelph Permeameter testing on the East Dam crest inside excavated test pit, 1.25 m below the ground surface (GP17-WD-02)

Figure 20c. Guelph permeameters are used to measure the in-situ saturated hydraulic conductivity of the uncompacted cycloned sands that are used to raise the tailings dams. The as-built reports by AMEC (2016a) and Klohn Crippen Berger (2017b, 2018, 2019) document extensive testing of construction material. However, as the above photo of a Guelph permeameter in a test pit at a depth of 1.25 meters indicates, this testing has been carried out only on the material (uncompacted cycloned sand) that had been used to raise the tailings dams since the previous annual report. By contrast, there is essentially no documentation of any testing that occurred prior to 2015. Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current quality of testing and the pre-2015 testing, as well as the extensive construction that occurred prior to 2015, the category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Photo from Klohn Crippen Berger (2018).

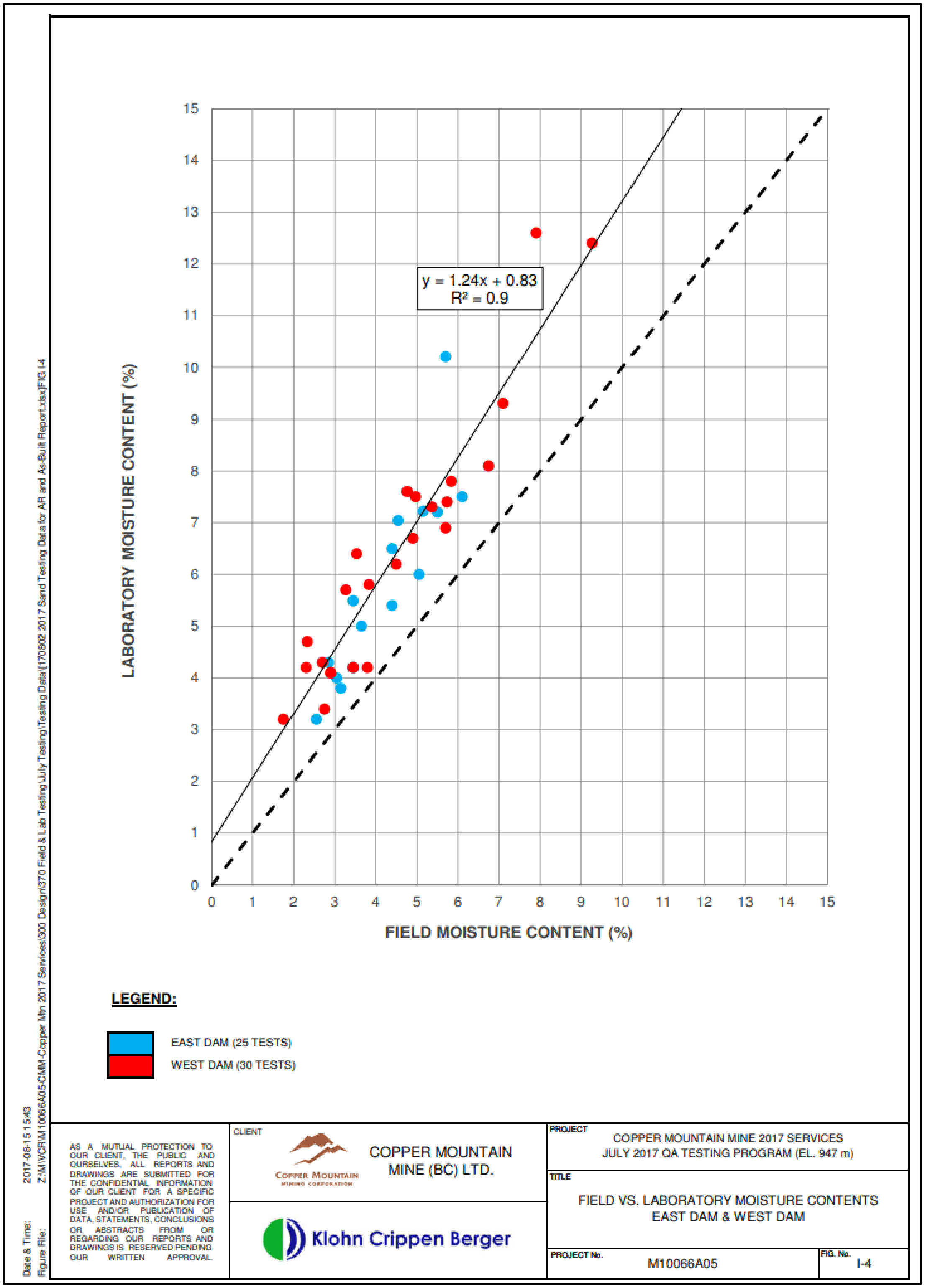


Figure 21. For the recent dam raises (since 2015), there has been an excellent correlation between moisture content measured in the field and lab. This generally fulfills the requirement of "Evaluate differences between laboratory test conditions and field conditions" for the category Above Average in the area Design – Testing for Level of Engineering. However, there is no such documentation for the construction prior to 2015. The category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Figure from Klohn Crippen Berger (2018).

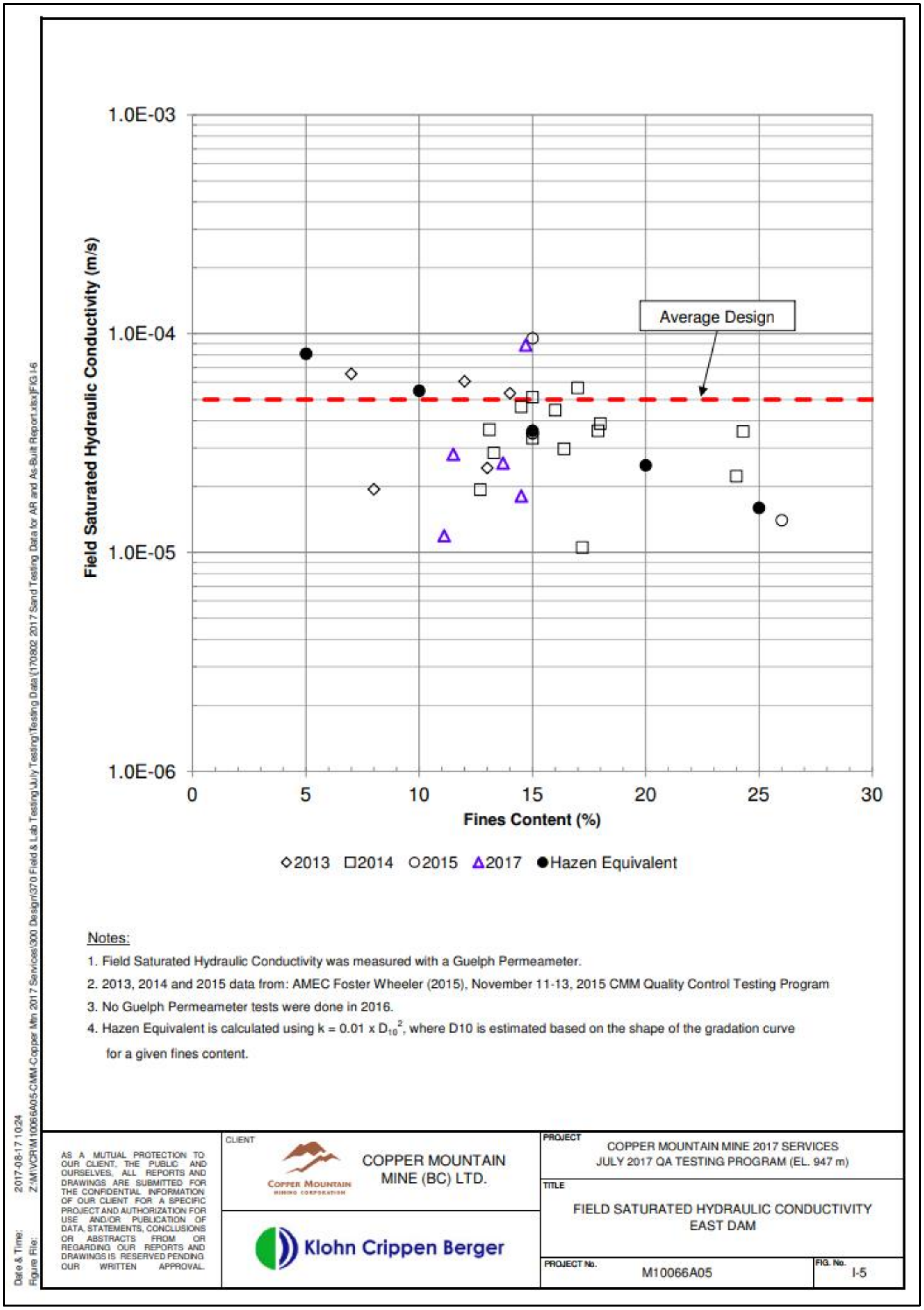


Figure 22. For the recent dam raises (since 2015), field saturated hydraulic conductivity (see Fig. 20c) was compared with the fines content. This generally fulfills the requirement of "Evaluate differences between laboratory test conditions and field conditions" for the category Above Average in the area Design – Testing for Level of Engineering. However, there is no such documentation for the construction prior to 2015. The category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Figure from Klohn Crippen Berger (2018).

Table 2.1 Index Properties of Triaxial Samples

Property	BK18-WD-01	BK18-ED-01
Laboratory Moisture Content	5.3%	4.9%
Fines Content[1]	13.3%	14.1%
Specific Gravity	2.82	2.80
Standard Proctor Maximum Dry Density	1721 kg/m^3	1680 kg/m^3
Optimum Moisture Content	16.0%	15.9%
Maximum Index Dry Density (ASTM D4253)	1651 kg/m^3	1641 kg/m^3
Minimum Index Dry Density (ASTM D4254)	1353 kg/m^3	1379 kg/m^3
Maximum Void Ratio[2]	1.1	1.0
Minimum Void Ratio[2]	0.7	0.7

Notes:

1. Fines Content = % passing the No. 200 sieve (by weight)
2. Void ratio $e = \frac{G\rho_w}{\rho_d} - 1$, where G = specific gravity, ρ_w = density of water, and ρ_d = dry density.

Figure 23a. Index properties were measured for the construction material (cycloned sand) used for the recent dam raises (since 2015). Thus, the requirement of "Run standard lab tests on undisturbed specimens" for the category Above Average in the area Design – Testing for Level of Engineering was fulfilled (see Table 1b). However, there is no such documentation for the construction prior to 2015. The category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Figure from Klohn Crippen Berger (2018).

Table 2.2 Summary of Undrained Triaxial Compression Test Results

Sample	Test Type	Initial Void Ratio	Consolidation Phase				Peak Secant Friction Angle[4] at Failure
			Vertical Stress, σ'_1 (kPa)	Cell Pressure, σ'_3 (kPa)	Mean Stress, σ'_m (kPa)[1]	Consolidated Void Ratio	
BK18-WD-01	CIUC	0.88	1000	1000	1,000	0.75	37.5°
	CAUC	0.87	2000	1000	1,500	0.73	38.0°
BK18-ED-01	CIUC	0.87	1500	1500	1,500	0.73	38.0°
	CAUC	0.87	1500	750	1,125	0.73	37.8°

Notes:

1. Mean Consolidation Stress is calculated using the following relationship:
   $\sigma'mean = (\sigma'1 + \sigma'3)/2$
2. Peak secant friction angle is calculated using the following relationship:
   $\varphi' = sin^{-1}(tan\,\alpha)$,
   where α = angle of inclination (degrees) of triaxial failure envelope (at maximum obliquity) on 'p-q' plot

Figure 23b. Shear strength parameters were measured for the construction material (cycloned sand) used for the recent dam raises (since 2015). According to Klohn Crippen Berger (2019), "The four triaxial specimens were prepared by the method of moist tamping at a moisture content of approximately 3% to a target initial dry density of about 1,500 kg/m^3 to simulate the mean minus one standard deviation of the average July 2018 field density testing data (KCB 2018). The prepared specimens were then saturated, consolidated (to simulate the expected consolidation pressure of the current shell below the ultimate dam), and sheared in undrained triaxial compression." Thus, the requirement of "Run lab tests on undisturbed specimens at field conditions" for the category Best in the area Design – Testing for Level of Engineering was fulfilled (see Table 1b). However, there is no such documentation for the construction prior to 2015. The category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Figure from Klohn Crippen Berger (2018).

It is important to note that all of the high standards that were met in the as-built reports beginning in 2015 refer only to the cycloned sands that were used for dam construction over the previous year. Even so, although each dam has been raised by about five meters per year, most of the test pits have been only about a meter deep (see Figs. 20a-c), thus testing only about 20-25% of the cycloned sand generated each year. However, there is a stark contrast between the high-quality testing that began in 2015 and the very limited testing that seems to have taken place prior to 2015. In particular, the 2021 Dam Safety Review described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980" (Tetra Tech, 2022).

In fact, according to the 2021 Dam Safety Review (Tetra Tech, 2022), it does not appear that construction was carried out in accordance with the design, even as late as 2014. According to Tetra Tech (2022), "A limit of approximately 61 m and 122 m on the upstream shift from their original centerline was recommended for the West and East Dam respectively (Klohn 1989). Based on AMEC's (2011) interpreted historic dam crest elevations, the final dam crest centerlines prior to reactivation were 90 m and 135 m upstream of the starter dam alignment for the West and East Dams respectively, suggesting that the recommended limit for upstream shift had been exceeded." Tetra Tech (2022) continued, "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed."

At the time of construction of the starter dikes for the East and West Dams in 1971, it was still not unusual for as-built drawings to be non-existent or to be simply duplicates of the design documents, with no regard as to the actual construction. According to Fell et al. (2015), "It is the authors' experience that embankment dams built in the 1950s to 1970s and even later have often not been constructed to the geometry shown on design drawings, or even to the as-constructed drawings. Also in many cases filters and transition zones have not been constructed as specified but have greater % fines and more plastic fines than specified." Dam safety and construction standards were considerably lower five decades ago, so that the lack of testing and construction in accordance with design in the early stages of the East and West Dams is not surprising. However, by 2014, it was unusual for dams to be constructed in discordance with the designs and without both design and as-built drawings. As explained in the preceding quote from Fell et al. (2015), the practice of constructing dams in discordance with the design was mostly over by the end of the 1970s. It should be noted that 2015 was the first year after the tailings dam disaster at Mount Polley in August 2014 and following the release of the expert panel review in January 2015 (Independent Expert Engineering Investigation and Review, 2015a-b).

innovation in geotechnical instrumentation

Calibration Record

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e-mail: info@rstinstruments.com • Website: www.rstinstruments.com

Vibrating Wire Piezometer

Customer:		Di-Corp - Calgary
Model:		VW2100-1.0
Serial Number:		VW39492
Mfg Number:		1627729
Range:		1.0 MPa
Temperature:		23.5 °C
Barometric Pressure:		996.5 millibars
Work Order Number:		211563
Cable Length:		100 meters
Cable Markings:		329736 m - 329836 m
Cable Colour Code:	Red / Black (Coil)	Green / White (Thermistor)
Cable Type:		EL380004
Thermistor Type:		3 kΩ

Applied Pressure (MPa)	First Reading (B units)	Second Reading (B units)	Average Reading (B units)	Calculated Linear (MPa)	Linearity Error (% FS)	Polynomial Error (% FS)
0.0	8933	8934	8934	0.001	0.13	0.01
0.2	8220	8221	8221	0.199	-0.05	-0.03
0.4	7502	7502	7502	0.399	-0.08	0.01
0.6	6783	6783	6783	0.599	-0.10	0.00
0.8	6060	6061	6061	0.800	-0.01	0.01
1.0	5336	5337	5337	1.001	0.11	-0.01
				Max. Error (%):	0.13	0.03

Linear Calibration Factor:	**C.F.=**	**0.00027795 MPa/B unit**
Regression Zero:	**At Calibration =**	**8938.2 B unit**
Temperature Correction Factor:	**Tk =**	**0.0003234 MPa/°C rise**

Polynomial Gage Factors (MPa) **A:** -6.8058E-10 **B:** -0.00026824 **C:** 2.4508

Pressure is calculated with the following equations:

Linear: $P(MPa) = C.F.(Li\text{-}Lc) - [Tk(Ti\text{-}Tc)] + [0.00010(Bi\text{-}Bc)]$

Polynomial: $P(MPa) = A(Lc)^2 + BLc + C + Tk(Tc\text{-}Ti) - [0.00010(Bc\text{-}Bi)]$

	Date (dd/mm/yy)	VW Readout Pos. B (Li)	Temp °C (Ti)	Baro (Bi)
Shipped Zero Readings:	20-Oct-16	8932	21.0	1013.8

Li, Lc = initial (at installation) and current readings
Ti, Tc = initial (at installation) and current temperature, in °C
Bi, Bc = initial (at installation) and current barometric pressure readings, in millibars
B units = B scale output of VW 2102, VW 2104, VW 2106 and DT 2011 readouts
B units = Hz^2 / 1000 ie: 1700Hz = 2890 B units

Technician: [redacted] Date: 20-Oct-16

This instrument has been calibrated using standards traceable to the NIST in compliance with ANSI Z540-1

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Document Number: ELL0143H

Figure 24. The 2016 Dam Safety Inspection report includes four certificates for factory calibration of piezometers. There is no mention of calibration of sensors in any of the other available documents except for recommendations that inclinometers should be re-calibrated annually. Thus, there has been only partial fulfillment of the requirement to “Calibrate equipment and sensors prior to testing program” for the category Best in the area Design – Testing for Level of Engineering (see Table 1b). The category for Level of Engineering in the area of Design – Testing was chosen as Average to Above Average (see Table 1b). Figure from Klohn Crippen Berger (2017).

An additional characteristic in the area Design – Testing relates to the calibration of instrumentation. The 2016 Dam Safety Inspection report (Klohn Crippen Berger, 2017; see Fig. 24) includes four certificates for factory calibration of piezometers. The only other mention of calibration of instruments in any of the available documents was the recommendation for "Annual re-calibration of RST inclinometer probe and reel prior to commencement of 2014 dam construction" with the acknowledgement that "The probe is recalibrated annually. This recommendation has been closed" (AMEC, 2014). The two subsequent Dam Safety Inspection reports (AMEC, 2016a; Klohn Crippen Berger, 2017b) further acknowledged the annual recalibration of the inclinometers. Inclinometers are used to monitor the displacement (motion) of the dam and are discussed further in the subsection Level of Engineering: Operation and Monitoring.

Due to the sparse mention of calibration in the available documents, including the lack of any mention of calibration of piezometers after factory calibration, the characteristic "Calibrate equipment and sensors prior to testing program" in the category Best for the area Design – Testing was assessed as "partially fulfilled" (see Table 1b). Due to the distinction between the pre-2015 construction and the construction that began in 2015, the following characteristics were assessed as "partially fulfilled" (see Table 1b):

1) Run lab tests on undisturbed specimens at field conditions (Best)
2) Run standard lab tests on undisturbed specimens (Above Average)
3) Evaluate differences between laboratory test conditions and field conditions (Above Average)

Due to the inadequate testing of the foundation materials, the following characteristics were assessed as "partially fulfilled" (see Table 1b):

1) Run index field tests (e.g., field vane, cone penetrometer) to detect all soft, wet, loose, high, or low permeability zones (Best)
2) Index tests on samples from site (Average)

Due to their absence from any available document, the following characteristics were assessed as "unfulfilled" (see Table 1b):

1) Run strength test along field effective and total stress paths (Best)
2) Measure pore pressure in strength tests (Above Average)

Based on the above assessments, the Level of Engineering for Design – Testing was assigned to the intermediate category Average to Above Average with a score of 0.5 (see Table 1b).

Level of Engineering: Design – Analyses and Documentation

The area Design – Analyses and Documentation largely relates to the quality of the input data that were used for calculation of the static factor of safety. The 2021 Dam Safety Review (Tetra Tech, 2022) did not carry out its own stability analyses, but reviewed stability analyses carried out by AMEC (2016b-c) and Klohn Crippen Berger (2020b (see Figs. 25a-b, 26a-b, and 27a-b). The stability analyses by AMEC (2016a-b) are the only analyses that have considered the factor of safety at the permitted dam crest elevation of 997 meters above sea level, which will be attained in 2027. By contrast, Klohn Crippen Berger (2020b) carried out stability analyses for the dam crest elevation that existed in 2020 (958 meters above sea level). Thus, the stability analyses by Klohn Crippen Berger (2020b) are already out of date, while the analyses AMEC (2016b-c) show the future static factor of safety of the East and West Dams. However, the stability analyses by AMEC (2016a-b) are not simply an advance in time and dam crest elevation of the stability analyses by Klohn Crippen Berger (2020b). The two sets of stability analyses use different input parameters, particularly with regard to the position of the water table.

Table 7-11: Material Parameters used for Stability Analyses by AMECFW (2016b and 2016c)

Material	Unit Weight (kN/m^3)	Friction Angle (°)[1]	Undrained Shear Strength Ratio (S_u/σ'_v)[1]
Foundation – Sand and Gravel	23	28[2]	-
Foundation – Lacustrine	18	11.3[3]	0.24[4]
Foundation – Glaciolacustrine	20	12[4]	-
Old Starter Dyke Fill / Talus Fill	21	36	-
Old Compacted CS (pre-2011) - *Zone I*	18	34	-
Old Uncompacted CS (pre-2011) - *Zone II*	20	32	-
Uncompacted CS (post-2011) - *Zone II*	18	32	-
Old Total Tailings (pre-2011) - *Zone III*	20	32	-
Total Tailings (post-2011) - *Zone III*	17	27	-

Notes:
1) Applied to both static and post-seismic analyses.
2) Friction angle reduced from 36° to account for presence of thin silty till layer encountered near the bedrock contact (AMECFW 2015).
3) For West Dam stability analysis only. The friction angle equivalent to s_u/σ_v' = 0.2. An undrained shear strength ratio of 0.2 was assigned to the LU, as DSS testing (discussed in Section 7.2.3.3) had not been completed before the West Dam stability analyses were undertaken; however, since the DSS testing indicated an undrained shear strength higher than 0.2, this should produce conservative results.
4) Used for East Dam stability analysis only.

Figure 25a. The stability analyses carried out by AMEC (2016b-c) assumed a unit weight for the uncompacted cycloned sand (construction material for the dam raises, corresponding to Uncompacted CS (post-2011) – Zone II in the table above) of 18 kN/m^3, although lower unit weights have been systematically measured. According to Tetra Tech (2022), "Field density testing is carried out throughout the year as part of the QA/QC program. Field density testing uses a portable nuclear gage and is completed both on surface and in test pits between 1.0 and 1.5 m deep [see Fig. 20b]. Results from the last 5 years indicate that the average field dry density ranges from 1530 to 1600 kg/m^3 and wet density ranges from 1640 to 1740 kg/m^3. These densities correspond to a maximum wet unit weight of 17 kN/m^3. Recent seismic response and stability assessments have utilized a higher unit weight (18 kN/m^3). The impact of using a higher unit weight on the results of these analyses should be checked." A higher unit weight could either decrease the factor of safety through increasing the gravitational stress on the dam raises or increase the factor of safety through increasing the normal (perpendicular) stress across possible failure surfaces. AMECFW (2016b) and AMECFW (2016c) correspond to AMEC (2016b) and AMEC (2016c), respectively, in this report. The long form of kN/m^3 is kilonewtons per cubic meter. Table from Tetra Tech (2022).

The input parameters for shear strength and density were reasonably similar for the stability analyses by AMEC (2016b-c) and Klohn Crippen Berger (2020b) (see Figs. 25a-b). The post-2011 construction material was called "Uncompacted CS [Cycloned Sands] (pre-2011) - Zone II" by AMEC (2016b-c) and was assigned a unit weight of 18 kilonewtons per cubic meter (corresponding to a density of 1835 kilograms per cubic meter) (see Fig. 25a). The post-2011 construction material was called "Uncompacted Cycloned Sand" by Klohn Crippen Berger (2020b) and was assigned an unit weight of 20 kilonewtons per cubic meter (corresponding to a density of 2039 kilograms per cubic meter) (see Fig. 25b). The 2021 Dam Safety Review (Tetra Tech, 2022) critiqued both assumptions as being systematically higher than the observed densities. According to Tetra Tech (2022), "Field density testing is carried out throughout the year as part of the QA/QC program. Field density testing uses a portable nuclear gage and is completed both on surface and in test pits between 1.0 and 1.5 m deep [see Fig. 20b]. Results from the last 5 years indicate that the average field dry density ranges from 1530 to 1600 kg/m^3 and wet density ranges from 1640 to 1740 kg/m^3. These densities correspond to a maximum wet unit weight of 17 kN/m^3. Recent seismic response and stability assessments have utilized a higher unit weight (18 kN/m^3). The impact of using a higher unit weight on the results of these analyses should be checked." Of course, the critique is even more applicable to the stability analyses by Klohn Crippen Berger (2020b), which assumed an even higher density (unit weight) for the post-2011 construction material. A higher density for the cycloned sand could decrease the factor of safety through increasing the gravitational stress on the dam raises. A higher density could also increase the factor of safety through increasing the normal (perpendicular) stress across possible failure surfaces, which would increase the friction across those surfaces and thus constrain slippage along the surfaces.

Table 7-12: Material Parameters used for Stability Analyses by KCB (2020c and 2020d)

Material		Unit Weight (kN/m^3)	Friction Angle[1] (°)[1]		Undrained Shear Strength Ratio (S_u/σ'_v)	
Foundation	Glaciofluvial/Fluvial Sand and Gravel	23	36		-	
	Lacustrine Silt/Clay	18	-		*Static:* 0.24	*Post-Eq:* 0.21
	Glaciolacustrine Clay	20	12		-	
	Bedrock	Impenetrable				
Dam Fills	Old Starter Dyke Fill / Talus Fill	21	35		-	
	Compacted Cyclone Sand	18	34		-	
	Uncompacted Cyclone Sand	20	*σ'_v < 1500 kPa:* 35	*σ'_v > 1500 kPa:* 32	-	
	Total Tailings	17	31		*Post-Eq: σ'_v < 1000 kPa: 0.07*[2]	*Post-Eq: σ'_v > 1000 kPa: 0.22*[2]
	Sand and Gravel Drainage	23	36		-	
	Rockfill	20	36		-	

Notes: Post-Eq = Post-Earthquake; *σ'_v = effective vertical stress.*

1) Applied to both static and post-seismic analyses unless otherwise indicated.
2) Represents liquified (S_u/σ'_v = 0.07) and strain-softened tailings (S_u/σ'_v = 0.22).

Figure 25b. The stability analyses carried out by Klohn Crippen Berger (2020a-b) assumed a unit weight for the uncompacted cycloned sand (construction material for the dam raises, corresponding to Uncompacted Cyclone Sand in the table above) of 20 kN/m^3, although lower unit weights have been systematically measured. According to Tetra Tech (2022), "Field density testing is carried out throughout the year as part of the QA/QC program. Field density testing uses a portable nuclear gage and is completed both on surface and in test pits between 1.0 and 1.5 m deep [see Fig. 20b]. Results from the last 5 years indicate that the average field dry density ranges from 1530 to 1600 kg/m^3 and wet density ranges from 1640 to 1740 kg/m^3 . These densities correspond to a maximum wet unit weight of 17 kN/m^3. Recent seismic response and stability assessments have utilized a higher unit weight (18 kN/m^3). The impact of using a higher unit weight on the results of these analyses should be checked." The preceding quote principally refers to Fig. 24b, which assumes a unit weight for the uncompacted cyclone sand of 18 kN/m^3, but should apply even more so to the table above, which assumes an even higher unit weight of 20 kN/m^3. A higher unit weight could either decrease the factor of safety through increasing the gravitational stress on the dam raises or increase the factor of safety through increasing the normal (perpendicular) stress across possible failure surfaces. KCB (2020c) and KCB (2020d) correspond to Klohn Crippen Berger (2020a) and Klohn Crippen Berger (2020b), respectively, in this report. The long form of kN/m^3 is kilonewtons per cubic meter. Table from Tetra Tech (2022).

Table 7-14: East Dam Stability Assessment Summary

Scenario	Section	Method	2D/3D	Phreatic Surface	Failure Surface	FOS
AMECFW (2016b) - Model Elevation = 997 m (currently permitted elevation)						
Static (EOC)	A2	Morgenstern-Price	2D	About 10 m above interface between tailings and uncompacted cyclone sands and between compacted and uncompacted cyclone sand interface (from AMEC (2011) EOC seepage modelling)	Through uncompacted cyclone sands and lacustrine layer, starting about two thirds of the way up dam face.	1.3
Static (Long-Term)	A2		2D	Along tailings/cyclone sand interface, slope up at 3.5H:1V through post-2011 tailings (from AMEC (2011) seepage modelling)	Through uncompacted cyclone sands and lacustrine layer, starting about halfway up dam face.	1.4
Post-Seismic	A2		2D		Through uncompacted cyclone sands and lacustrine layer, starting about halfway up dam face.	**1.4**

Figure 26a. The stability analysis of the East Dam by AMEC (2016b) is the only analysis that has considered the factor of safety at the permitted dam crest elevation of 997 meters above sea level, which will be attained in 2027. AMEC (2016b) calculated static factors of safety FS of FS = 1.3 and FS = 1.4 for two different assumptions regarding the position of the phreatic surface (water table). Neither assumption considered the high phreatic surface that could occur in response to an extreme storm event, such as the Probable Maximum Flood. Both calculated factors of safety are less than the minimum FS = 1.5 required by mining regulations in British Columbia (Ministry of Energy and Mines (British Columbia), 2016; see Fig. 8). The two calculations also distinguish between the factor of safety at the EOC (end of construction) and the long-term factor of safety. Construction (dam raising) tends to generate excess pore pressures that are dissipated in the long term, so that long-term factors of safety tend to be higher than factors of safety calculated for the end of construction. For tailings dams that are continually raised, the increase in factor of safety over the long term is not relevant, which is why Ministry of Energy and Mines (British Columbia) (2016) requires the same minimum FS = 1.5 for both the end of construction and the long term (see Fig. 8). Table from Tetra Tech (2022).

Table 7-13: West Dam Stability Assessments Summary

Loading Condition	Section[1]	Method	2D/3D	Phreatic Surface	Failure Surface	FOS
AMECFW (2016c) - Model Elevation = 997 m (currently permitted elevation)						
Static (EOC)	B1	Bishop / Jambu Simplified	2D	From AMEC (2011) EOC seepage modelling (location not shown in documentation provided)	Through uncompacted cyclone sands and lacustrine layer	1.3
Static (EOC)	B1		3D		Through uncompacted cyclone sands and lacustrine layer	**1.7**
Post-Seismic	B1		3D	Along tailings/cyclone sand interface, slope up at 3.5H:1V through post-2011 tailings (from AMEC (2011) seepage modelling).	Through uncompacted cyclone sands and lacustrine layer	**1.7**

Figure 26b. The stability analysis of the West Dam by AMEC (2016c) is the only analysis that has considered the factor of safety at the permitted dam crest elevation of 997 meters above sea level, which will be attained in 2027. AMEC (2016b) calculated static factors of safety FS of FS = 1.3 for a two-dimensional model and FS = 1.7 for a three-dimensional model. Three-dimensional models tend to produce higher factors of safety because they can take into account stabilization by the valley walls. In this case, according to the 2021 Dam Safety Review, the three-dimensional calculation did not properly take into account the actual width of the weak glaciolacustrine layer in the foundation. For both calculations, the position of the assumed phreatic surface (water table) was not documented. It is unlikely that the assumed phreatic surface took into account the high phreatic surface that could occur in response to an extreme storm event, such as the Probable Maximum Flood. The calculated factor of safety FS = 1.3 is less than the minimum FS = 1.5 required by mining regulations in British Columbia (Ministry of Energy and Mines (British Columbia), 2016; see Fig. 8). Both calculations are for the factor of safety at the EOC (end of construction). Construction (dam raising) tends to generate excess pore pressures that are dissipated in the long term, so that long-term factors of safety tend to be higher than factors of safety calculated for the end of construction. For tailings dams that are continually raised, the increase in factor of safety over the long term is not relevant, which is why Ministry of Energy and Mines (British Columbia) (2016) requires the same minimum FS = 1.5 for both the end of construction and the long term (see Fig. 8). Table from Tetra Tech (2022).

KCB (2020d) - Model Elevation = 958 m (2020 elevation)						
Static (EOC / Long-Term)	A1	Morgenstern-Price	2D	Three different piezometric lines (PL) used. ▪ PL-1: Primarily along tailings/cyclone sand interface. Applied to post-2011 tailings. ▪ PL-2: Same as PL-1, but lower in the tailings. Applied to pre-2011 tailings. ▪ PL-3: Sloping up from through Starter Dam and tailings at approximate 3.5H:1V. Applied to all non-tailings materials.	Through tailings and lacustrine layer	**1.6**
Static (Long-Term)	A2				Along tailings/cyclone sand interface, then through tailings and lacustrine layer.	**1.9**
Post-Seismic	A1				Through tailings and lacustrine layer	**1.2**
Post-Seismic	A2				Through tailings and lacustrine layer.	**1.4**
NOTES: ▪ *Modelling carried out using SLOPE/W (by GeoSlope International, now Seequent Ltd)* ▪ *No changes to model geometry from KCB (2020c) except dam height and location of LU as discussed in the comments*						

Notes: EOC = End of Construction; FOS = Factor of Safety; R_u = Excess Pore Pressure factor
1. Section ID of approximate 2D section used, as shown on Figure 2 of the 2020 DSI (provided in Appendix B of this report for reference).
2. Provided in Appendix F.

Figure 27a. Klohn Crippen Berger (2020b) [KCB (2020d) in the above table] carried out a stability analysis of the East Dam for the dam crest elevation that existed in 2020 (958 meters above sea level). The stability analysis resulted in a static factor of safety FS of FS = 1.6 for a cross-section A1 for both EOC (end of construction) and long-term and FS = 1.9 for a cross-section A2 only for the long term. Construction (dam raising) tends to generate excess pore pressures that are dissipated in the long term, so that long-term factors of safety tend to be higher than factors of safety calculated for the end of construction. For tailings dams that are continually raised, the increase in factor of safety over the long term is not relevant, which is why Ministry of Energy and Mines (British Columbia) (2016) requires the same minimum FS = 1.5 for both the end of construction and the long term (see Fig. 8). The 2021 Dam Safety Review critiqued the assumptions made for the position of the phreatic surface (piezometric line or water table), claiming that the assumed phreatic surface was too low, resulting in calculated factors of safety that were too high. Note that AMEC (2016b) assumed a phreatic surface that was "about 10 m above interface between tailings and uncompacted cyclone sands" (see Fig. 26a), while Klohn Crippen Berger (2020b) assumed that the phreatic surface was "primarily along tailings/cyclone sand interface" (see figure above). In particular, the 2021 Dam Safety Review claimed that the assumed phreatic surface was not justified by the piezometric data. According to Tetra Tech (2022), "Given the relatively sparse data upstream of the dam crest, we do not consider the lower projections of Piezometric No. 2 and No. 3 – which are up to 250 m upstream of the most recently collected data – to be justified. While KCB (2020d) notes that long term analyses should consider more conservative phreatic surfaces, Tetra Tech suggests that, even for short term analyses, the lower phreatic surfaces upstream of the dam crest (through the tailings) represented by Piezometric No. 2 and No. 3, are not sufficiently supported by data in this area." The 2021 Dam Safety Review also noted that the assumed phreatic surface did not consider the high phreatic surface that could occur in response to an extreme storm event, such as the Probable Maximum Flood. Table from Tetra Tech (2022).

Other critiques of the input parameters as being assumed, as opposed to measured, relate mostly to the foundation materials, which is consistent with the lack of characterization of the foundation that was described in the subsection Level of Engineering: Design – Investigation. According to Tetra Tech (2022), "For the Lacustrine Silt and Clay Unit (LU) … a unit weight of 18 kN/m^3 was adopted for design … but field densities for this material have not been measured. No laboratory testing was carried out to determine the hydraulic conductivity or unit weight of the LU … No advanced testing was completed on the fluvial and glaciofluvial sands and gravels … For the reactivation design, AMEC (2011) assumed a reference peak drained friction angle 42° at 100 kPa with a 6° reduction in strength for each 10-fold increase in overburden pressure. For subsequent analyses, this appears to have been simplified such that [a] single design friction angle of 36° is assigned to the glaciofluvial sands and gravels … It is unclear why the fluvial and glaciofluvial materials were assigned differing hydraulic conductivities, given their generally similar make-up … No advanced testing has been completed on the glaciolacustrine clay." For clarification, hydraulic conductivity impacts the factor of safety through its effect on the expected position of the water table in the tailings management facility. Tetra Tech (2022) emphasized that the shear strength parameters of the glaciolacustrine clay were not actually measured, but were assumed based upon measurements of glaciolacustrine clay units at other mine sites in British Columbia. Even so, the logic for applying measurements at other mine sites to the Copper Mountain site was unclear to the authors of the 2021 Dam Safety Review. According to Tetra Tech (2022), “For design, the glaciolacustrine clay was assumed to be pre-sheared and [a] residual … friction angle of 12° was adopted by AMECFW (2016b) and KCB (2020c) [Klohn Crippen Berger, 2020b], which is considered mathematically equivalent to an undrained shear strength ratio of 0.21 (AMECFW 2016b). The soil strength was chosen based on lower bound values from laboratory testing and back-calculations of shear strength in glaciolacustrine clays underlying tailings facilities at other BC sites (Kemess South Mine, Mount Polley Mine, Highland Valley Copper Mine) (AMECFW 2015). However, the mathematical equivalency of the undrained shear strength ratio of 0.21 to a friction angle of 12° is unclear.”

KCB (2020d) - Model Elevation = 958 m (2020 elevation)						
Static (EOC / Long-Term)	B1	Morgenstern-Price	2D	Three different piezometric lines (PL)used. PL-1: Primarily along tailings/cyclone sand interface. Applied to post-2011 tailings. PL-2: Primarily along tailings/cyclone sand interface, but lower in the tailings than PL-1. Applied to pre-2011 tailings. PL-3: Sloping up from top of Starter Dam through tailings at approximate 4H:1V. Applied to all non-tailings materials.	Through tailings and lacustrine layer	**1.6**
Post-Seismic			2D		Through tailings and lacustrine layer	**1.2**

NOTES:

- *Modelling carried out using SLOPE/W (by GeoSlope International, now Seequent Ltd)*
- *No changes to model geometry from KCB (2020c) except dam height*

Figure 27b. Klohn Crippen Berger (2020b) [KCB (2020d) in the above table] carried out a stability analysis of the West Dam at the dam crest elevation that existed in 2020 (958 meters above sea level). The stability analysis resulted in a factor of safety FS of FS = 1.6 for both EOC (end of construction) and long-term. Construction (dam raising) tends to generate excess pore pressures that are dissipated in the long term, so that long-term factors of safety tend to be higher than factors of safety calculated for the end of construction. For tailings dams that are continually raised, the increase in factor of safety over the long term is not relevant, which is why Ministry of Energy and Mines (British Columbia) (2016) requires the same minimum FS = 1.5 for both the end of construction and the long term (see Fig. 8). The 2021 Dam Safety Review critiqued the assumptions made for the position of the phreatic surface (piezometric line or water table), claiming that the assumed phreatic surface was too low, resulting in calculated factors of safety that were too high. In particular, the 2021 Dam Safety Review claimed that the assumed phreatic surface was not justified by the piezometric data. According to Tetra Tech (2022), “Given the relatively sparse data upstream of the dam crest, we do not consider the lower projections of Piezometric No. 2 and No. 3 – which are up to 250 m upstream of the most recently collected data – to be justified. While KCB (2020d) notes that long term analyses should consider more conservative phreatic surfaces, Tetra Tech suggests that, even for short term analyses, the lower phreatic surfaces upstream of the dam crest (through the tailings) represented by Piezometric No. 2 and No. 3, are not sufficiently supported by data in this area.” The 2021 Dam Safety Review also noted that the assumed phreatic surface did not consider the high phreatic surface that could occur in response to an extreme storm event, such as the Probable Maximum Flood. Table from Tetra Tech (2022).

Besides the difference of 39 meters in the dam crest elevation, the principal difference between the stability analyses by AMEC (2016b-c) and Klohn Crippen Berger (2020b) was that Klohn Crippen Berger (2020b) systematically assumed lower water tables. For the East Dam, AMEC (2016b) assumed a water table that was “about 10 m above interface between tailings and uncompacted cyclone sands” (Tetra Tech, 2022; see Fig. 26a), while Klohn Crippen Berger (2020b) assumed that the water table was “primarily along tailings/cyclone sand interface” (Tetra Tech, 2022) for both the East and West Dams (see Figs. 27a-b). It has already been noted in the subsection Level of Engineering: Design – Investigation that the 2021 Dam Safety Review (Tetra Tech, 2022) did not regard the low water table that was assumed by Klohn Crippen Berger (2020b) to be justified by the sparse piezometric data. Unfortunately, the water table that was assumed for the West Dam by AMEC (2016c) is completely unknown. Tetra Tech (2022) described the assumed water table simply as "location not shown in documentation provided" (see Fig. 26b). The 2021 Dam Safety Review (Tetra Tech, 2022) noted that none of the existing stability analyses has considered the high water table that could occur in response to an extreme storm event, such as the Probable Maximum Flood (see Figs. 26a-b and 27a-b).

Despite the higher dam crest elevation that was assumed by AMEC (2016b-c), the stability analyses carried out by AMEC (2016b-c) resulted in lower factors of safety, most likely due to the assumption of a higher water table. For the East Dam, AMEC (2016b) calculated an end-construction static factor of safety of FS = 1.3 and a long-term static factor of safety of FS = 1.4. The two calculations were based on the same two-dimensional cross-section, but different assumptions regarding the position of the water table (see Fig. 26a). It must be noted that both calculated static factors of safety are less than the minimum static factor of safety of FS = 1.5 that is required by the British Columbia Ministry of Energy and Mines (2016) (see Fig. 8). In other words, although the tailings dam at the Copper Mountain mine may (or may not) meet the minimum required factor of safety at the present elevation, they are being raised to an elevation at which the minimum factor of safety would not be satisfied. Based on the available information, it is not possible to determine the dam crest elevation at which the East Dam will cease to have the minimum factor of safety of FS = 1.5, even if the East Dam has the required minimum factor of safety at the present time. The 2021 Dam Safety Reviews listed as a deficiency or non-conformance the fact that "intermediate geometries between the current and maximum East and West Dam shape were not documented in stability assessments" (Tetra Tech, 2022). As expected, the calculated factor of safety is lower for the end-of-construction period (FS = 1.3) than for the long-term period (FS = 1.4). It has already been noted that the British Columbia Ministry of Energy and Mines (2016) requires the same minimum factor of safety for the end-of-construction period as for the long-term period (see Fig. 8) and that the long-term behavior is not relevant for tailings dams that are being continuously raised.

For the West Dam, AMEC (2016c) calculated end-of-construction static factors of safety of FS = 1.3 for a two-dimensional model and FS = 1.7 for a three-dimensional model (see Fig. 26b). Three-dimensional models tend to produce higher factors of safety because they can take into account stabilization by the valley walls. In this case, according to the 2021 Dam Safety Review (Tetra-Tech, 2022), the three-dimensional calculation did not properly take into account the actual width of the weak glaciolacustrine layer in the foundation. According to Tetra Tech (2022), the "3D model used a 200 m wide linearly extruded 2D section, where LU [Lacustrine Silt and Clay Unit] was 110 m wide." For the East Dam, Klohn Crippen Berger (2020b) calculated a static factor of safety of FS = 1.6 for one particular two-dimensional cross-section, for both the end-of-construction and long-term periods (see Fig. 27a). For another two-dimensional cross-section, Klohn Crippen Berger (2020b) calculated a static factor of safety of FS = 1.9 only for long-term behavior (see Fig. 27a). For the West Dam, Klohn Crippen Berger (2020b) calculated a static factor of safety of FS = 1.6 for a single two-dimensional cross-section, for both the end-of-construction and long-term periods (see Fig. 27b). It should be noted that nothing in the discussion in the 2021 Dam Safety Review (Tetra Tech, 2022) of the stability analyses by AMEC (2016b-c) and Klohn Crippen Berger (2020b) suggests that the calculated factors of safety are overly conservative. For that reason, all calculated factors of safety should be regarded as most-likely values.

For the assignment of the Level of Engineering to a category in the area Design – Analyses and Documentation, the primary issue is whether the input parameters for the stability analysis were measured, inferred from index tests, or only assumed. Since the input parameters were a mix of the preceding, including parameters that were measured, but inadequately measured, all of the characteristics below were assessed as "partially fulfilled" (see Table 1c):

1) Determine FS using effective stress parameters based on measured data (geometry, strength, pore pressure for site (Best)
2) Determine FS using effective stress parameters and pore pressures (Above Average)
3) Rational analyses using parameters inferred from index tests (Average)
4) Approximate analyses using assumed parameters (Poor)

The following characteristics were assessed as "unfulfilled" because there is no indication that they were carried out at all (see Table 1c):

1) Consider field stress path in stability determination (Best)
2) Prepare flow net for instrumented sections (Best)
3) Predict pore pressure and other relevant performance parameters (e.g., stress, deformation, flow rates for instrumented section) (Best)
4) Adjust for significant differences between field stress paths and stress path implied in analysis that could affect design (Above Average)

The Best category has three additional characteristics in the area of Design – Analyses and Documentation (see Table 1c). The characteristic "Have design report clearly document parameters and analysis used for design" in the Best category was assessed as "partially fulfilled" (see Table 1c). Multiple dam safety inspection reports and dam safety reviews have various versions of a table with the heading "Design Basis" (e,g., see Fig. 28 from Klohn Crippen Berger (2021)). However, what would be considered to be an adequate Design Basis Report would be a far more detailed document. For example, Johndrow et al. (2022) include a five-page outline of all the required information in an adequate Design Basis Report.

The characteristic "No errors and omissions" was assessed as "partially fulfilled or unknown" (see Table 1c). Strictly speaking, the author does not know whether any mistakes were made in the calculation of the factor of safety. In addition, it is difficult to reconcile the concept of "no errors or omissions" with the large number of questionable assumptions that were pointed out in the 2021 Dam Safety Review (Tetra Tech, 2022). Moreover, the missing water table in the stability analysis for the West Dam by AMEC (2016c) certainly counts as an "omission." If the characteristic "No errors or emissions" is meant to be taken literally, then it should be assessed as "unfulfilled." The final characteristic in the Best category in the area of Design – Analyses and Documentation is "Peer review." The Copper Mountain mine set up an Independent Tailings Review Board (ITRB) in 2016 (Copper Mountain Mine (BC) Ltd., 2016. Although there are no publicly available records of the deliberations or recommendations of the ITRB, the characteristic is assessed as "fulfilled." Based on the above assessments, the Level of Engineering for Design – Analyses and Documentation was assigned to the category Average with a score of 0.6 (see Table 1c).

Table 2.1 Design Basis

Category	Item	Value/Rating
Tailings Storage	Production Rate	40,000 tonnes per day [1]
	Total Required Storage	420.6 million tonnes [5]
Dam Consequence Classification (CDA 2013)	Tailings Management Facility	East Dam, Extreme West Dam, Extreme
Flood Management	Inflow Design Flood (IDF) Storage	72-hour Probable Maximum Flood (PMF)
	Minimum Freeboard above IDF Level for Wave Run-up	2 m
Dam Final Elevation, Crest Width, and Downstream Slope	East Dam, West Dam	Crest Elevation, 997 m Crest Width, 40 m Downstream Slope, 2.5 H:1V
Geotechnical Stability	Seismicity	10,000-year Earthquake (Magnitude = 7.0, PGA = 0.38 g) [4]
	Limit Equilibrium Factor of Safety	Static, End of Construction > 1.5 [2] Static, Long term > 1.5 [2] Seismic, Pseudo-static > 1.0 Seismic, Post-earthquake > 1.2
Pond Management	Minimum Beach Width	East Dam ≥ 300 m West Dam ≥ 300 m
Tailings Deposition Slope	Above Water	0.5%
	Below Water	0.2% [3]

Notes:

1. The reactivation design was based on 35,000 tpd. Since 2015, the mill production rate has increased to 40,000 tpd. Annual mass balance and construction staging is now based on 40,000 tpd. CMML plans on increasing mill production rate to 45,000 tpd with the installation of Ball Mill 3, scheduled for Q4 2021.
2. Based on HSRC (MEMPR 2016) recommendation.
3. On average, the first 25 m to 50 m of tailings below water is deposited at approximately 1%, based on bathymetry data from October 2020.
4. Based on site specific seismic hazard assessment, using 2005 National Building Code of Canada (NBCC) attenuation relationships (AMEC 2011).
5. Includes 190.6 Mt deposited in the historic TMF prior to reactivation in 2011 and 230 Mt accommodated by the reactivation design to El. 997.0 m

Figure 28. Multiple dam safety inspection reports and dam safety reviews have various versions of the table above. The table above only partially fulfills the requirement to "Have a design report clearly document parameters and analyses used for design" for the category Best in the area Design – Analyses and Documentation for Level of Engineering (see Table 1c). An adequate Design Basis Report would be a far more detailed document. For example, Johndrow et al. (2022) include a five-page outline of all the required information in an adequate Design Basis Report. Table from Klohn Crippen Berger (2021).

Level of Engineering: Construction

Much of the discussion in the subsection Level of Engineering: Design – Testing also applies to the area of Construction. In particular, there is considerable contrast between the high standards for quality assurance and quality control, as well as detailed construction reports, that were carried out beginning in 2015 and the much lower standards, especially the lack of conformance of construction to design, that took place prior to 2015. For example, Fig. 29 taken from the 2016 Dam Safety Inspection report (Klohn Crippen Berger, 2017b) illustrates the effectiveness of the cyclones at reducing the content of fine-grained tailings to the design mean fines content of 15% in the cycloned sands that are used to construct the dam raises. Figs. 30a-b taken from the 2018 Dam Safety Inspection report (Klohn Crippen Berger, 2019) illustrate the detailed and extensive quality assurance and quality control that were routine beginning in 2015. These figures and many similar examples from the Dam Safety Inspection reports beginning in 2015 are consistent with the characteristics of "construction control tests by qualified engineers and technicians" and "construction report clearly documents construction activities" for Level of Engineering in the category Best in the area of Construction (see Table 1d).

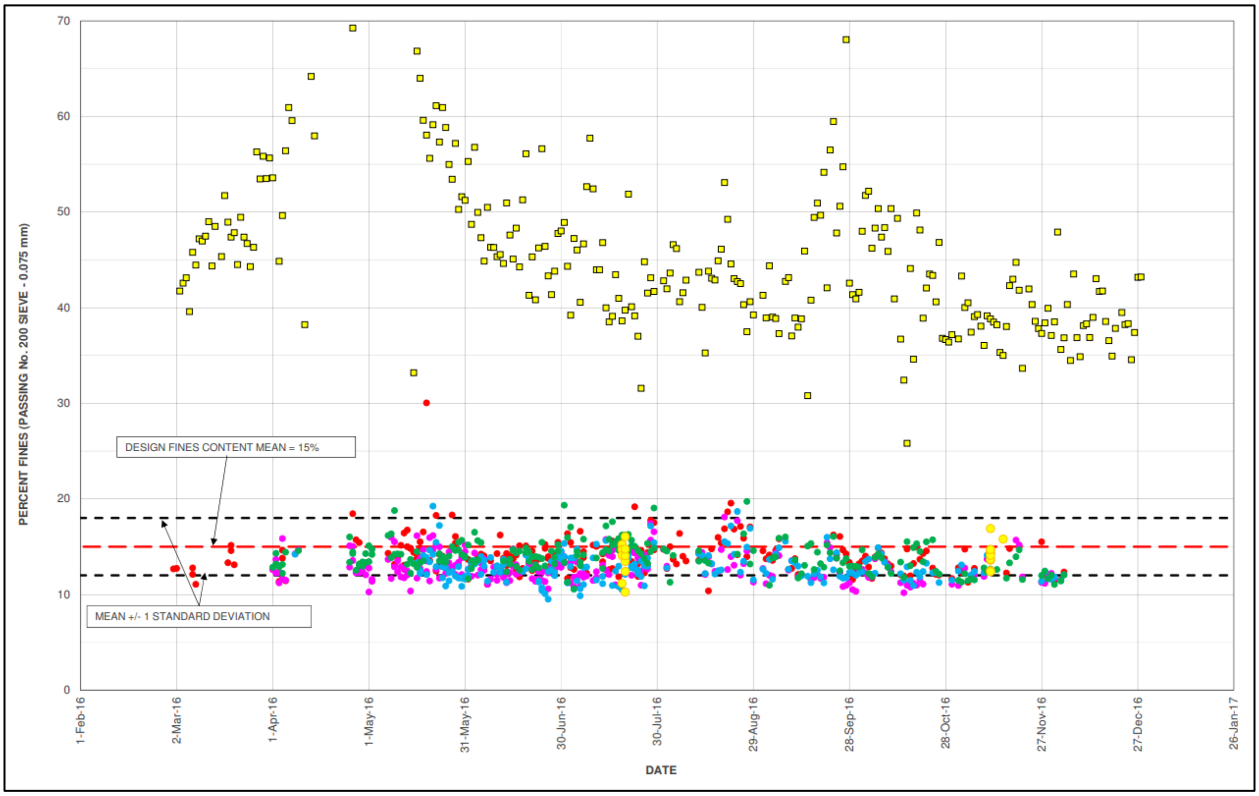


Figure 29. The above figure illustrates the effectiveness of the cyclones at reducing the content of fine-grained tailings to the design mean fines content of 15% in the cycloned sands that are used to construct the dam raises (see Fig. 16). In the figure, the gold squares indicate the fines content of the tailings as they arrive from the ore processing plant, while the colored circles indicate the outputs of the various cyclones. The figure is consistent with the characteristics of "construction control tests by qualified engineers and technicians" and "construction report clearly documents construction activities" for Level of Engineering in the category Best in the area Construction (see Table 1d). However, such documentation is available only for the dam raises that occurred beginning in 2015. By contrast, Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current and the pre-2015 quality control and construction reporting, and taking into account the extensive construction that occurred prior to 2015, as well as the ongoing lack of full-time supervision by a qualified engineer (see Fig. 31), the category for Level of Engineering in the area of Construction was chosen as Above Average (see Table 1d). Figure from Klohn Crippen Berger (2017b).

Table IV-7 Summary of 2018 QA Test Results for East Dam

	Test / Properties	Unit	No. of Tests	Minimum	Maximum	Mean[1]	Standard Deviation, SD	COV[2]	Target Mean Value
Field and Laboratory Test Results									
1	Field Dry Density[3],[4]	kg/m³	34	1,483	1,698	1,549	46	3%	1,550
2	Field Wet Density[4]	kg/m³	34	1,566	1,910	1,688	72	4%	-
3	Field Moisture Content	%	42	3	11	7	2	29%	12
4	Field Saturated Hydraulic Conductivity[5]	m/s	5	1.3×10^{-5}	5.8×10^{-5}	3.2×10^{-5}	2.0×10^{-5}	63%	5×10^{-5}
5	Laboratory Moisture Content[6]	%	43	5	15	9	2	27%	-
6	Fines Content[7]	%	38	10	21	14	3	20%	15
7	Specific Gravity	-	2	2.80	2.83	2.82	0.02	1%	-
8	Standard Proctor Maximum Dry Density (SPMDD)	kg/m³	2	1,680	1,685	1,683	4	0.2%	-
9	Standard Proctor Optimum Moisture Content (OMC)	%	2	16	19	17	2	11%	-
10	Minimum Index Dry Density	kg/m³	2	1,332	1,379	1,356	33	2%	-
11	Maximum Index Dry Density	kg/m³	2	1,620	1,642	1,631	15	1%	-
Estimated Relative Density and Void Ratio Results[3],[4]									
12	Relative Density	%	34	46	93	62	10	17%	50
13	Void Ratio	-	34	0.66	0.90	0.83	0.05	6%	-

Notes:

1. Mean is the arithmetic mean.
2. Coefficient of Variability, COV = SD / Mean, a normalized measure of variability.
3. Field dry density estimated based on laboratory moisture content.
4. Seven density test results from track-packed crest surface and one density test result on fresh cyclone sand are excluded from the statistical summary. See Section IV-9.3.2 for details.
5. Field saturated hydraulic conductivity was measured using a Guelph Permeameter.
6. Since laboratory moisture was not measured for some density test samples, it was estimated using the trendline in Figure IV-4, as discussed in Section IV-9.3.3.3. Both measured and estimated moisture contents are included in the statistical summary.
7. Including No. 200 wash sieves performed on Particle Size Distribution (GS-series), Guelph Permeameter (GP-series) and Specific Gravity samples (BK-series).

Figure 30a. The above figure illustrates the quality assurance that is carried out on the cycloned sand that is used to construct the dam raises for the East Dam and is consistent with the characteristics of "construction control tests by qualified engineers and technicians" and "construction report clearly documents construction activities" for Level of Engineering in the category Best in the area Construction (see Table 1d). However, such documentation is available only for the dam raises that occurred beginning in 2015. By contrast, Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current and the pre-2015 quality control and construction reporting, and taking into account the extensive construction that occurred prior to 2015, as well as the ongoing lack of full-time supervision by a qualified engineer (see Fig. 31), the category for Level of Engineering in the area of Construction was chosen as Above Average (see Table 1d). Figure from Klohn Crippen Berger (2019).

Table IV-8 Summary of 2018 QA Test Results for West Dam

	Test / Properties	Unit	No. of Tests	Minimum	Maximum	Mean[1]	Standard Deviation, SD	COV[2]	Target Mean Value
Field and Laboratory Test Results									
1	Field Dry Density[3],[4]	kg/m³	45	1,459	1,651	1,554	48	3%	1,550
2	Field Wet Density[4]	kg/m³	45	1,573	1,900	1,699	74	4%	-
3	Field Moisture Content	%	53	3	17	7	3	39%	12
4	Field Saturated Hydraulic Conductivity[5]	m/s	4	2.0×10^{-5}	3.2×10^{-5}	2.5×10^{-5}	5.4×10^{-6}	21%	5×10^{-5}
5	Laboratory Moisture Content[6]	%	54	5	19	9	3	33%	-
6	Fines Content[7]	%	46	9	21	14	3	20%	15
7	Specific Gravity	-	2	2.79	2.82	2.81	0.02	1%	-
8	Standard Proctor Maximum Dry Density (SPMDD)	kg/m³	2	1,665	1,721	1,693	40	2%	-
9	Standard Proctor Optimum Moisture Content (OMC)	%	1	16	18	17	1	7%	-
10	Minimum Index Dry Density	kg/m³	2	1,296	1,354	1,325	41	3%	-
11	Maximum Index Dry Density	kg/m³	2	1,570	1,651	1,610	57	4%	-
Estimated Relative Density and Void Ratio Results[3],[4]									
12	Relative Density	%	45	40	84	63	11	18%	50
13	Void Ratio	-	45	0.71	0.94	0.82	0.06	7%	-

Notes:

1. Mean is the arithmetic mean.
2. Coefficient of Variability, COV = SD / Mean, a normalized measure of variability.
3. Field dry density estimated based on laboratory moisture content.
4. Five density test results from track-packed crest surface and three from fresh cyclone sand are excluded from the statistical summary. See Section IV-9.3.2 for details.
5. Field saturated hydraulic conductivity was measured using a Guelph Permeameter.
6. Since laboratory moisture was not measured for some density test samples, it was estimated using the trendline in Figure IV-4, as discussed in Section IV-9.3.3.3. Both measured and estimated moisture contents are included in the statistical summary.
7. Including No. 200 wash sieves performed on Particle Size Distribution (GS- series), Guelph Permeameter (GP-series) and Specific Gravity samples (BK-series).

Figure 30b. The above figure illustrates the quality assurance that is carried out on the cycloned sand that is used to construct the dam raises for the West Dam and is consistent with the characteristics of "construction control tests by qualified engineers and technicians" and "construction report clearly documents construction activities" for Level of Engineering in the category Best in the area Construction (see Table 1d). However, such documentation is available only for the dam raises that occurred beginning in 2015. By contrast, Tetra Tech (2022) described the construction material for the starter dams (constructed in 1971) as "random" and stated that "there is limited data on the compacted cycloned sands that were used to construct the dam shell prior to 1980." In fact, prior to 2015, it does not appear that construction was even carried out in accordance with the design. According to Tetra Tech (2022), "The reactivation design also called for a rockfill zone at the toe of the dams, extending back to the pre-2011 dam slope and 40 to 50 m above the dam toe. However, there is no indication that this was ever built; based on as-built records (KCB 2021b) [Klohn Crippen Berger (2021) in this report], the zone where rockfill was proposed to be used was constructed of cyclone sand … The reactivation design also called for slope drains, similar in design to the 2014 crest drain (AMEC 2011), to be laid along the downstream slopes of the dams, but there is no evidence that these were installed." Based on the contrast between the current and the pre-2015 quality control and construction reporting, and taking into account the extensive construction that occurred prior to 2015, as well as the ongoing lack of full-time supervision by a qualified engineer (see Fig. 31), the category for Level of Engineering in the area of Construction was chosen as Above Average (see Table 1d). Figure from Klohn Crippen Berger (2019).

Table IV-1 Construction Monitoring Responsibilities (Source: OMS Manual)

Criticality	Description	CMML Responsibility	Engineer of Record Responsibility	Example of Activity
Routine	Construction activity requiring minimal periodic oversight with routine testing, primarily for record rather than construction control purposes.	All construction monitoring and QC testing, unless Engineer of Record specifically requested to assist with certain testing.	Review CMML construction progress reports, review activities during site visits, and liaise with CMML personnel over any issues identified by CMML or by Engineer of Record in site visits/report reviews.	▪ Cycloned sand deposition. ▪ Placement of Zone 3 general rock fill. ▪ All other construction activities not specifically referenced above.
Significant	Construction activity requiring intermittent, but not continual, construction monitoring, with QA/AC testing being used for acceptance (or rejection) of the constructed work.	All construction monitoring and QA testing. Regular inspections required. Liaise weekly with Engineer of Record during these activities, and coordinate Engineer of Record QA site visits.	Engineer of Record to make periodic site visits to view construction, and to do QA field testing and acquire samples for QA laboratory testing.	▪ Approval of Zone 2 transition rock fill prior to placement of Zone 3 generalrock fill. ▪ Construction of slope drains. ▪ Wolfe Creek diversion/relocation works except for flow-through draincomponent.
Critical	Construction activity requiring full time supervision, where inadequate construction could potentially result in significant flaws negatively affecting the performance of the dams, and resulting in construction out of conformance with design intent.	Continuous construction monitoring when Engineer of Record is not present. Coordinate Engineer of Record site visits for inspections. CMML responsible for QC testing.	Engineer of Record to be present on continuous or intermittent basis as agreed with CMML based on specific construction activity and progress. QA field and laboratory testing.	▪ Foundation preparation and approvals for extension of the downstream toe of the dam (i.e. foundations for the rockfill toe berms). ▪ Approval of Zone 1 filter prior to placement of rockfill or cyclone sand covering Zone 1. ▪ Inspections ofabutment areas at dam crest for any areas requiring filter placement to prevent potentialinternal erosion. ▪ Installation ofpiezometers andinclinometers. ▪ Geomembrane linerplaced in advance of Wolfe Creek relocation. ▪ Construction of crest drains. ▪ Flow through draincomponent of Wolfe Creek relocation.

Figure 31. The above table from the OMS (Operations, Maintenance and Surveillance) Manual clarifies that "routine" and "significant" construction does not include full-time supervision by a qualified engineer, which would be required for Level of Engineering in the category Best in the area Construction (see Table 1d). The only example as to what constituted "critical" construction was "The 2015 raising of the TMF to El. 936 m was relatively routine in nature with the exception of periodic QA field and lab testing of cycloned sand production. The critical item requiring direct Amec Foster Wheeler supervision was the inspection of the abutment contact areas prior to sand placement. This was performed in conjunction with the periodic site visits performed by Amec Foster Wheeler throughout the 2015 construction period" (AMEC, 2016a). On that basis, as well as the lack of quality control and detailed construction reports for pre-2015 construction (see Figs. 20a-c), the category for Level of Engineering in the area of Construction was chosen as Above Average (see Table 1d). Table from Klohn Crippen Berger (2019).

The area of Construction also relates to the degree of supervision of construction by a qualified engineer, especially in terms of whether the supervision is full-time or part-time. Fig. 31, which is taken from the OMS (Operations, Maintenance and Surveillance) Manual, as reported in the 2018 Dam Safety Inspection report (Klohn Crippen Berger, 2019), indicates that "routine" and "significant" construction do not include full-time supervision by a qualified engineer, which would be required for Level of Engineering in the category Best in the area Construction (see Table 1d). According to the OMS Manual, "critical" construction is "construction activity requiring full time supervision, where inadequate construction could potentially result in significant flaws negatively affecting the performance of the dams, and resulting in construction out of conformance with design intent" (Klohn Crippen Berger, 2019; see Fig. 31). In all of the available documentation, the only example as to what would constitute "critical" construction is from the 2015 Dam Safety Inspection report (AMEC, 2016a). According to AMEC (2016a), "The 2015 raising of the TMF to El. 936 m was relatively routine in nature with the exception of periodic QA field and lab testing of cycloned sand production. The critical item requiring direct Amec Foster Wheeler supervision was the inspection of the abutment contact areas prior to sand placement. This was performed in conjunction with the periodic site visits performed by Amec Foster Wheeler throughout the 2015 construction period."

Taking into account the contrast between the construction beginning in 2015 and the pre-2015 construction, the following characteristics were assessed as "partially fulfilled" (see Table 1d):

1) Construction control tests by qualified engineers and technicians (Best)
2) No errors or omissions (Best and Above Average)
3) Construction report clearly documents construction activities (Best)

Note that if the requirement for "no errors or omissions" were taken fully literally, the characteristic should be assessed as "unfulfilled," due to the numerous non-conformances between construction and design in the pre-2015 period. Due to the ongoing lack of full-time construction supervision, the characteristic "Full time supervision by qualified engineer" in the Best category was assessed as "unfulfilled," while the characteristic "Part time supervision by qualified engineer" in the Above Average category was assessed as "fulfilled." Based on the above assessments, the Level of Engineering for Construction was assigned to the category Above Average with a score of 0.4 (see Table 1d).

Level of Engineering: Operation and Monitoring

The area Operation and Monitoring largely deals with the instrumentation of the tailings management facility. By compiling the data from the annual Dam Safety Inspection reports (AMEC, 2014, 2016a; Klohn Crippen Berger, 2017b, 2018, 2019, 2021, 2022a), each of which recounts the number of functional instruments at the time of inspection, it can be seen that since 2015 the number of functional piezometers at the Copper Mountain Tailings Management Facility has varied between 37 and 46, and was at an all-time low at the end of 2021 (see Fig. 32). It appears that non-functional instruments have been replaced in spurts, for example, between 2015 and 2016 and between 2017 and 2018, and then allowed to again fall into disrepair, especially from 2020 to 2021 (see Fig. 32). The critique by the 2021 Dam Safety Review (Tetra Tech, 2022) of the lack of functional piezometers and the resultant inability to adequately define the water table for calculation of the factor of safety has already been recounted in the subsection Level of Engineering: Design – Investigation.

The decline in the number of functional inclinometers is even more dramatic. Since 2015 the number of functional inclinometers at the Copper Mountain Tailings Management Facility has steadily dropped until, out of seven installed inclinometers, only one functional inclinometer remained at the end of 2021 (see Fig. 33). According to the 2021 Dam Safety Review, "The T2 triggers for the inclinometers should be reviewed, as there are so few inclinometers remaining that they cannot realistically be grouped … There are no functional inclinometers at the West Dam" (Tetra Tech, 2022). As expected, the 2021 Dam Safety Review (Tetra Tech, 2022) listed the lack of functional inclinometers, especially at the West Dam, as a deficiency or non-conformance.

In the area of Operation and Monitoring, the Best category would require "no malfunctions" (see Table 1e). In fact, it is not all clear as to why the engineering team at the Copper Mountain mine needs annual dam safety inspections by an external consulting company to inform them that instruments are not functioning. On the other hand, the Above Average category would require "no uncorrected malfunctions." In other words, Above Average engineering would mean that non-functional instruments would be replaced or repaired as was deemed necessary by an external consulting company. Even this characteristic must be assessed as "unfulfilled" because of the way in which instruments are allowed to continue to fall into disrepair without maintenance or replacement, even as the lack of non-functional instruments is noted in the annual Dam Safety Inspection reports (see Figs. 32 and 33). On the other hand, Average engineering would be consistent with "no field measurements" at all (see Table 1e), which reinforces a previous point that Average engineering is appropriate for "unimportant or temporary facilities with low failure consequences" (see Table 1e). None of the available documents include any comparisons between predicted and measured performance (such as predictions of piezometric or inclinometer data).

Based on the above, all of the following characteristics were assessed as "unfulfilled" (see Table 1e):

1) Complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength) (Best)
2) No malfunctions (slides, cracks, artesian heads) (Best)
3) Continuous maintenance by trained crews (Best)
4) No uncorrected malfunctions (Above Average)
5) Routine maintenance (Above Average)

The characteristic "Periodic inspection by qualified engineer" in the category Above Average can be assessed as "fulfilled" due to inspections that occur at about three-month intervals that are described in some of the recent annual Dam Safety Inspection reports (AMEC, 2016a; Klohn Crippen Berger, 2017, 2018, 2019). The overall Level of Engineering in the area of Operation and Monitoring was assigned to the intermediate category Average to Above Average with a score of 0.5 (see Table 1e).

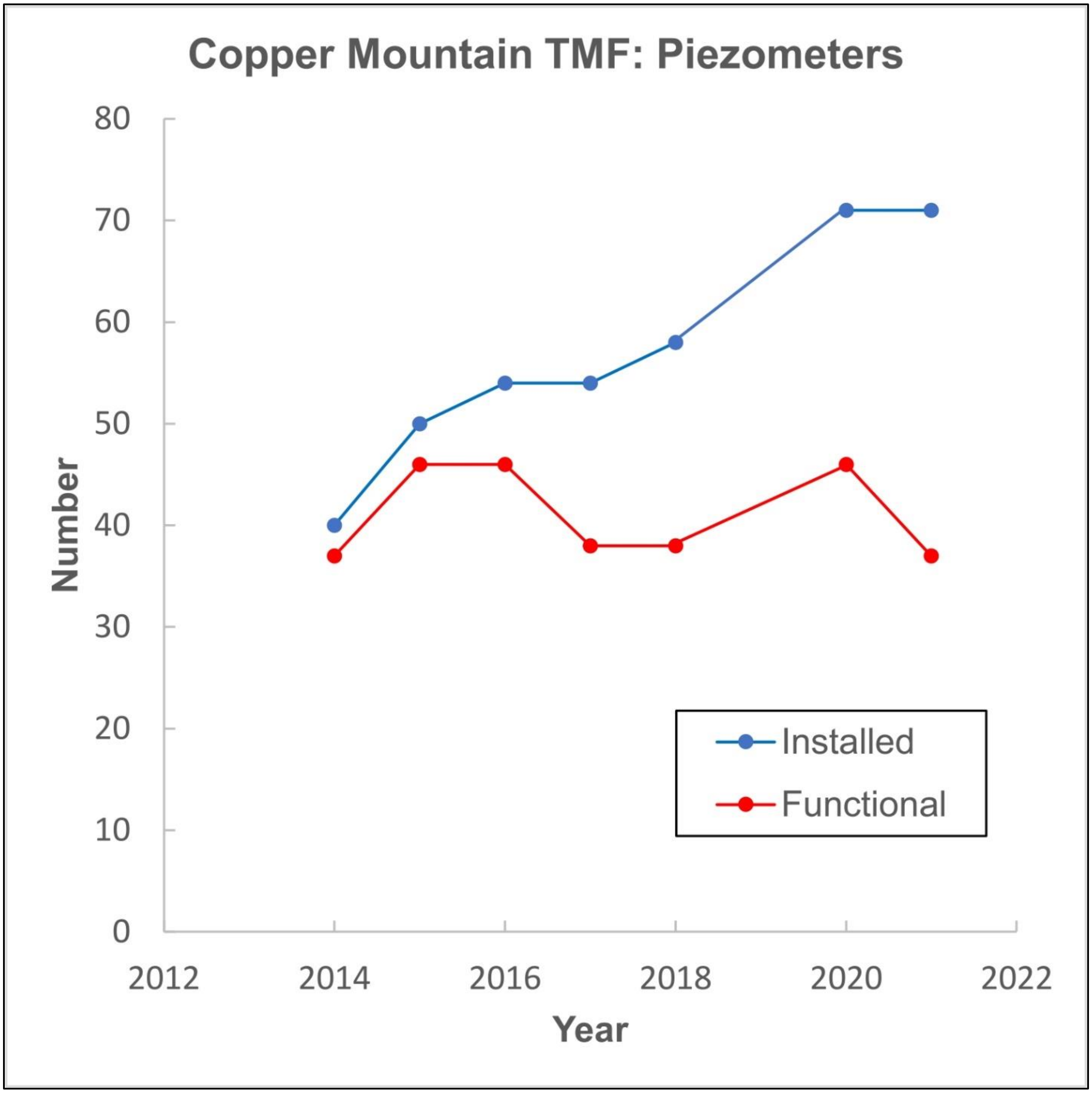


Figure 32. Since 2015 the number of functional piezometers at the Copper Mountain Tailings Management Facility has varied between 37 and 46, and was at an all-time low at the end of 2021. The 2021 Dam Safety Review critiqued the lack of piezometers and the resultant inability to adequately define the phreatic surface (water table) for calculation of the factor of safety (see Figs. 27a-b). The category Best for Level of Engineering in the area Operation and Monitoring would require "No malfunctions" and "Continuous maintenance by trained crews," implying that annual dam safety inspections should not report non-functional instrumentation (see Table 1e). The category Above Average would require "no uncorrected malfunctions," implying that non-functional instruments should be repaired or replaced. However, a characteristic of the category Average is "no field measurements," implying the absence of any piezometers. On the above basis, the category for Level of Engineering in the area of Operation and Monitoring was chosen as Average to Above Average (see Table 1e). The choice is also consistent with the lack of a "complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength, deformations)," which would be required by the category Best. Finally, the choice is consistent with the existence of both periodic and annual inspections by qualified engineers that is required by the categories Above Average and Average, respectively. Data from AMEC (2014, 2016a) and Klohn Crippen Berger (2017b, 2018, 2019, 2021, 2022a).

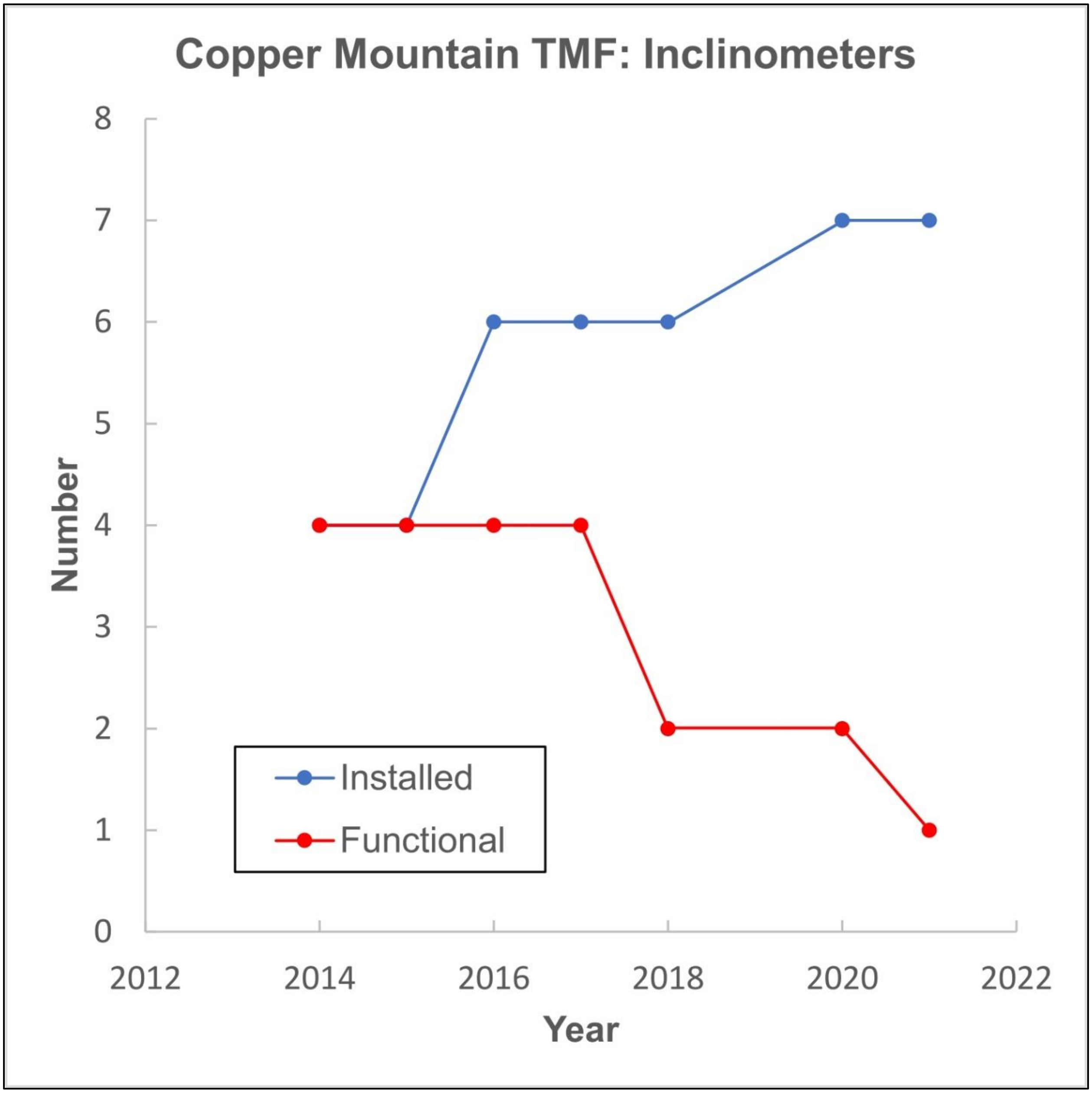


Figure 33. Since 2015 the number of functional inclinometers at the Copper Mountain Tailings Management Facility has steadily dropped until only one functional inclinometer remained at the end of 2021. The category Best for Level of Engineering in the area Operation and Monitoring would require "No malfunctions" and "Continuous maintenance by trained crews," implying that annual dam safety inspections should not report non-functional instrumentation (see Table 1e). The category Above Average would require "no uncorrected malfunctions," implying that non-functional instruments should be repaired or replaced. However, a characteristic of the category Average is "no field measurements," implying the absence of any piezometers. On the above basis, the category for Level of Engineering in the area of Operation and Monitoring was chosen as Average to Above Average (see Table 1e). The choice is also consistent with the lack of a "complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength, deformations)," which would be required by the category Best. Finally, the choice is consistent with the existence of both periodic and annual inspections by qualified engineers that is required by the categories Above Average and Average, respectively. Data from AMEC (2014, 2016a) and Klohn Crippen Berger (2017b, 2018, 2019, 2021, 2022a).

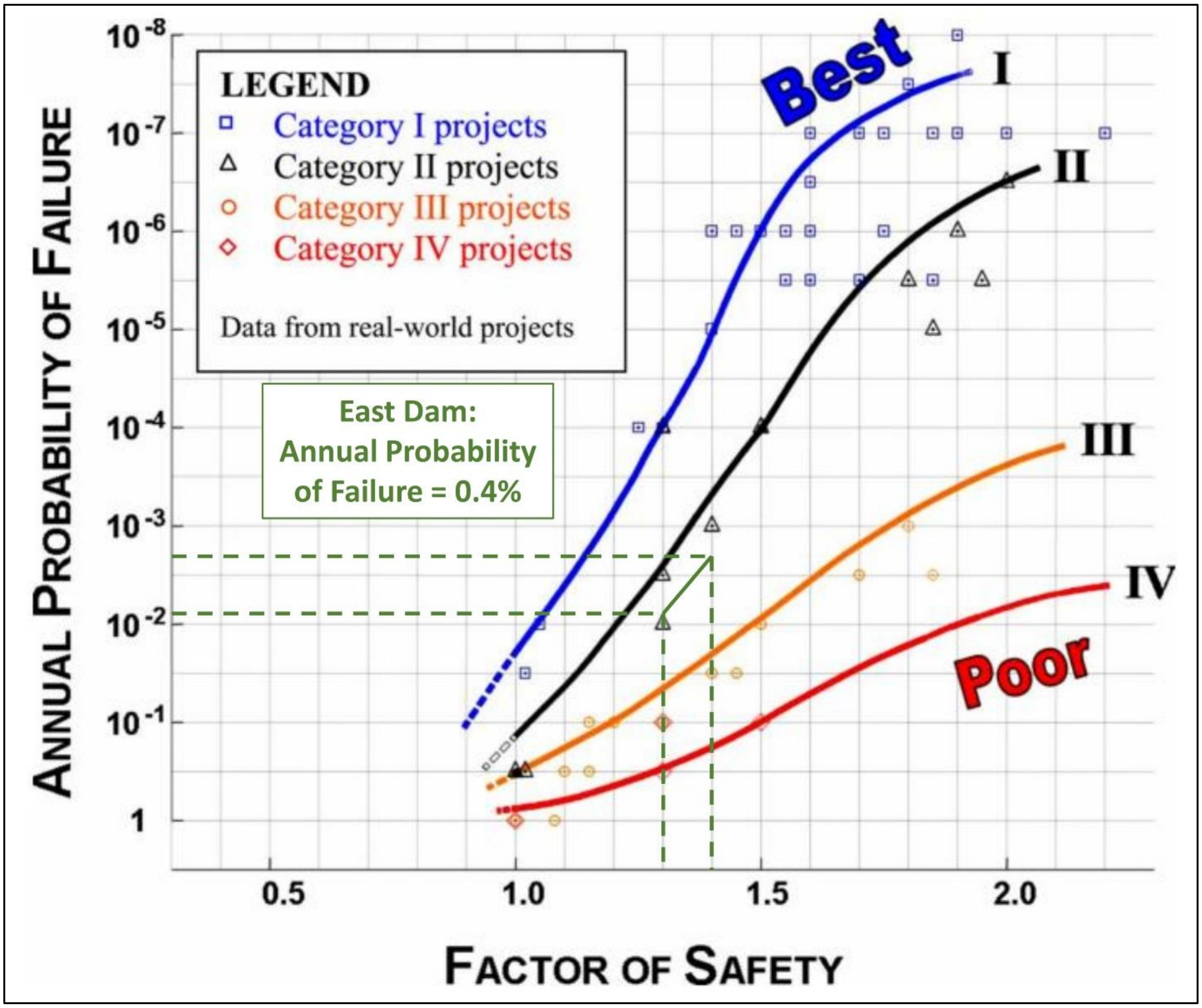


Figure 34a. Based upon calculated factors of safety of FS = 1.3 and FS = 1.4 (see Fig. 26a) and an overall Level of Engineering of 2.4 (where Above Average = 2 and Average = 3) (see Tables 1a-e), the annual probability of failure of the East Dam was estimated in the range 0.2-0.8% with a best estimate of 0.4%. Based upon the best estimate for the annual probability of failure of the West Dam as 0.05% (see Fig. 34b), the best estimate for the annual probability of failure of the Copper Mountain Tailings Management Facility is 0.45%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.1-1% (1 in 1000 to 1 in 100). Figure modified from Silva et al. (2008).

Estimation of Annual Probability of Failure

The scores assessed for the five areas sum to an overall Level of Engineering of 2.4, where Above Average has a score of 2 and Average has a score of 3. Thus, the Level of Engineering is between Above Average (which would be appropriate for ordinary facilities) and Average (which would be appropriate for temporary or unimportant facilities), although slightly closer to Above Average. Based upon the preceding Level of Engineering and calculated factors of safety of FS = 1.3 and FS = 1.4 for the permitted dam crest elevation (see Fig. 26a), the annual probability of failure of the East Dam was estimated in the range 0.2-0.8% with a best estimate of 0.4% (see Fig. 34a). Based upon the same Level of Engineering and calculated factors of safety of FS = 1.3 and FS = 1.7 for the permitted dam crest elevation (see Fig. 26b), the annual probability of failure of the West Dam was estimated in the range 0.004-0.8% with a best estimate of 0.05% (see Fig. 34b). By summing the best estimate of 0.4% for the East Dam and 0.05% for the West Dam, the best estimate for the annual probability of failure of the Copper Mountain Tailings Management Facility is 0.45%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.1-1% (1 in 1000 to 1 in 100).

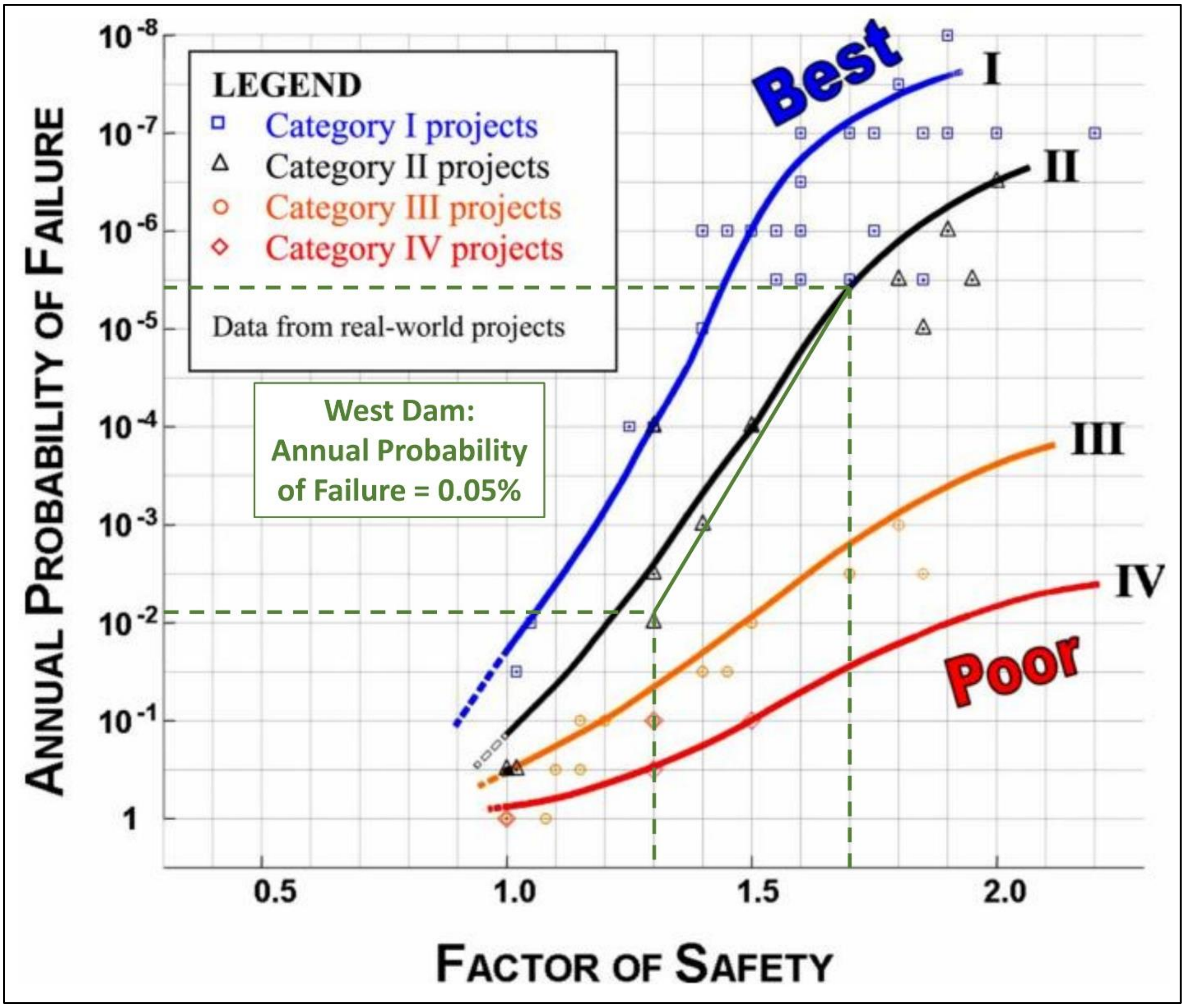


Figure 34b. Based upon calculated factors of safety of FS = 1.3 and FS = 1.7 (see Fig. 26b) and an overall Level of Engineering of 2.4 (where Above Average = 2 and Average = 3) (see Tables 1a-e), the annual probability of failure of the West Dam was estimated in the range 0.004-0.8% with a best estimate of 0.05%. Based upon the best estimate for the annual probability of failure of the East Dam as 0.4% (see Fig. 34a), the best estimate for the annual probability of failure of the Copper Mountain Tailings Management Facility is 0.45%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.1-1% (1 in 1000 to 1 in 100). Figure modified from Silva et al. (2008).

DISCUSSION

Comparison with Estimate based on Historical Record

The estimate of 0.45% (with a range of 0.1-1% or 1 in 1000 to 1 in 100) for the annual probability of failure for the Copper Mountain Tailings Management Facility based on the Silva-Lambe-Marr method can now be compared with an estimate based on the historical record of tailings dam failures. The first study of the historical record was carried out by Davies (2002) who reported, "Based on this larger database, it can be concluded that for the past 30 years, there have been approximately 2 to 5 'major' tailings dam failure incidents per year … If one assumes a worldwide inventory of 3500 tailings dams, then 2 to 5 failures per year equates to an annual probability somewhere between 1 in 700 [0.14%] to 1 in 1750 [0.06%]. This rate of failure does not offer a favourable comparison with the less than 1 in 10,000 [0.01%] that appears representative for conventional dams." The estimate by Davies (2002) was based on incomplete databases for both tailings dams and tailings dam failures. It is now generally believed that there are 20-30,000 tailings dams in the world. It is noteworthy that the annual probability of failure of 0.01% (1 in 10,000) for water-retention dams is sufficiently widely-accepted that it was used as a calibration point for earthen structures with a factor of safety of FS = 1.5 and Level of Engineering in the category Above Average by Silva et al. (2008) (see Fig. 10).

Despite the inadequate databases used by Davies (2002), later estimates have reinforced the annual probability of failure for tailings dams in the vicinity of 0.1% (1 in 1000), or ten times the annual probability of failure for water-retention dams. For global tailings dam failures in the decade around 1979, global tailings dam failures in the decade around 1999, US tailings dam failures in the decade around 1979, and US tailings dam failures in the decade around 1999, Oboni et al. (2014), Caldwell et al. (2015) and Oboni and Oboni (2020) found annual probabilities of failure of 0.13%, 0.02%, 0.07%, and 0.08%, respectively. Emerman (2020, 2021) found minimum annual probabilities of failure of 0.06% both for Peru during 1952-2019 and for Brazil during 1986-2019. The estimates by Emerman (2020, 2021) were lower bounds because it was assumed that all tailings dams in existence at the time of the study had been in existence since the first documented tailings dam failure in each country (1952 for Peru and 1986 for Brazil). Finally, Taguchi (2014) carried out a fault tree analysis in which historical failure frequencies were assigned to sequences of events that could end in catastrophic failure of a tailings dam. Taguchi (2014) found an annual probability of failure of 0.1% for tailings that were deposited as a slurry and 0.02% for tailings that were dewatered prior to deposition. The tailings at the Copper Mountain are deposited as a slurry (see Figs. 16 and 17a-b), so that the upper estimate (0.1%) by Taguchi (2014) would be more applicable.

The most accurate estimate of the annual probability of failure of tailings dams was carried out by Independent Expert Engineering Investigation and Review Panel (2015a-b), who were able to take into account the number of tailings dam failures, the number of existing tailings dams, and the years that each tailings dam had been in existence. The work by Independent Expert Engineering Investigation and Review Panel (2015a-b) is also the most relevant to this report since it was carried out for British Columbia and thus integrates the climate and seismicity of British Columbia, as well as the levels of engineering and of regulation that have been typical for the province. According to Independent Expert Engineering Investigation and Review Panel (2015a), "Active tailings dams were tracked through the years from Ministry of Energy and Mines (MEM) records. In the 46-year period since 1969, there was a total of 4,095 years of active operation and 7 failures, where failure is considered to be breach of the dam resulting in release of tailings and/or water. This corresponds to a failure frequency of 1.7×10^{-3} per dam per year. In other words, statistically there is approximately a 1-in-600 chance of a tailings dam failure in any given year, based on historical performance over the period of record." Independent Expert Engineering Investigation and Review Panel (2015b) defined an "active tailings dam" as "a tailings dam whose impoundment contains surface water," which does not necessarily mean that the tailings facility is still receiving additional tailings. Although Independent Expert Engineering Investigation and Review Panel (2015a-b) focused on active tailings dams, it should not be assumed that closed tailings dams are protected from failure. This subject was also investigated by one of the authors of Independent Expert Engineering Investigation and Review Panel (2015a-b) and will be further discussed in the subsection Long-Term Prospects for Tailings Dams at Copper Mountain Mine.

The historical failure frequency of 0.17% for tailings dams in British Columbia would correspond to an estimated annual probability of failure of 0.34% for the Copper Mountain Tailings Management Facility, which could fail due to failure of either the East Dam or the West Dam. The estimate is shockingly similar to the estimate of 0.45% that was found using the Silva-Lambe-Marr method. There are two interpretations of the similar results, both of which could be correct. The first interpretation is that the application of the Silva-Lambe-Marr method in this report is probably correct since the final result has been reinforced by a completely different methodology. The second interpretation is that the Level of Engineering for the tailings dams at the Copper Mountain mine (Average to Above Average) is simply typical for tailings dams in British Columbia. However, such "typical" engineering requires serious re-evaluation for tailings dams in the Extreme consequence category (potential loss of more than 100 lives in the event of dam failure). This is exactly the point made by Silva et al. (2010), who wrote, "Then there are those [engineering projects] requiring 'best' practices where the consequences of poor performance are very large … These are projects like … major dams."

Comparison with Canadian and U.S. Risk Guidelines

Annual probabilities of failure for the tailings dams at the Copper Mountain mine in the range 0.1-1% (1 in 1000 to 1 in 100) are now compared with dam safety guidelines in Canada and the USA, with particular emphasis on the potential for loss of life in the event of dam failure. According to the guidelines of the Canadian Dam Association (2013), an annual probability of dam failure of 0.1% (1 in 1000) is marginally acceptable (outside of the region "Additional risk control is required") only if dam failure would result in no more than one potential fatality, and broad acceptability would require an annual probability of failure no greater than 0.001% (1 in 100,000) (see Fig. 35a). The dam failure consequence category of the tailings dams at the Copper Mountain mine is Extreme, meaning that failure would result in the potential loss of more than 100 lives. For the minimum of 100 fatalities, marginal acceptability would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while broad acceptability would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000) (see Fig. 35a). On the above basis, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) should be entirely unacceptable in Canada. The region "Risk is tolerable, if ALARP" (see Fig. 35a) indicates that the risk is acceptable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to Canadian Dam Association

(2013), "The ALARP principle is based on the duty to reduce risks to life to the point where further risk reduction is impracticable or requires action that is grossly disproportionate in time, trouble, and effort to the reduction of risk achieved."

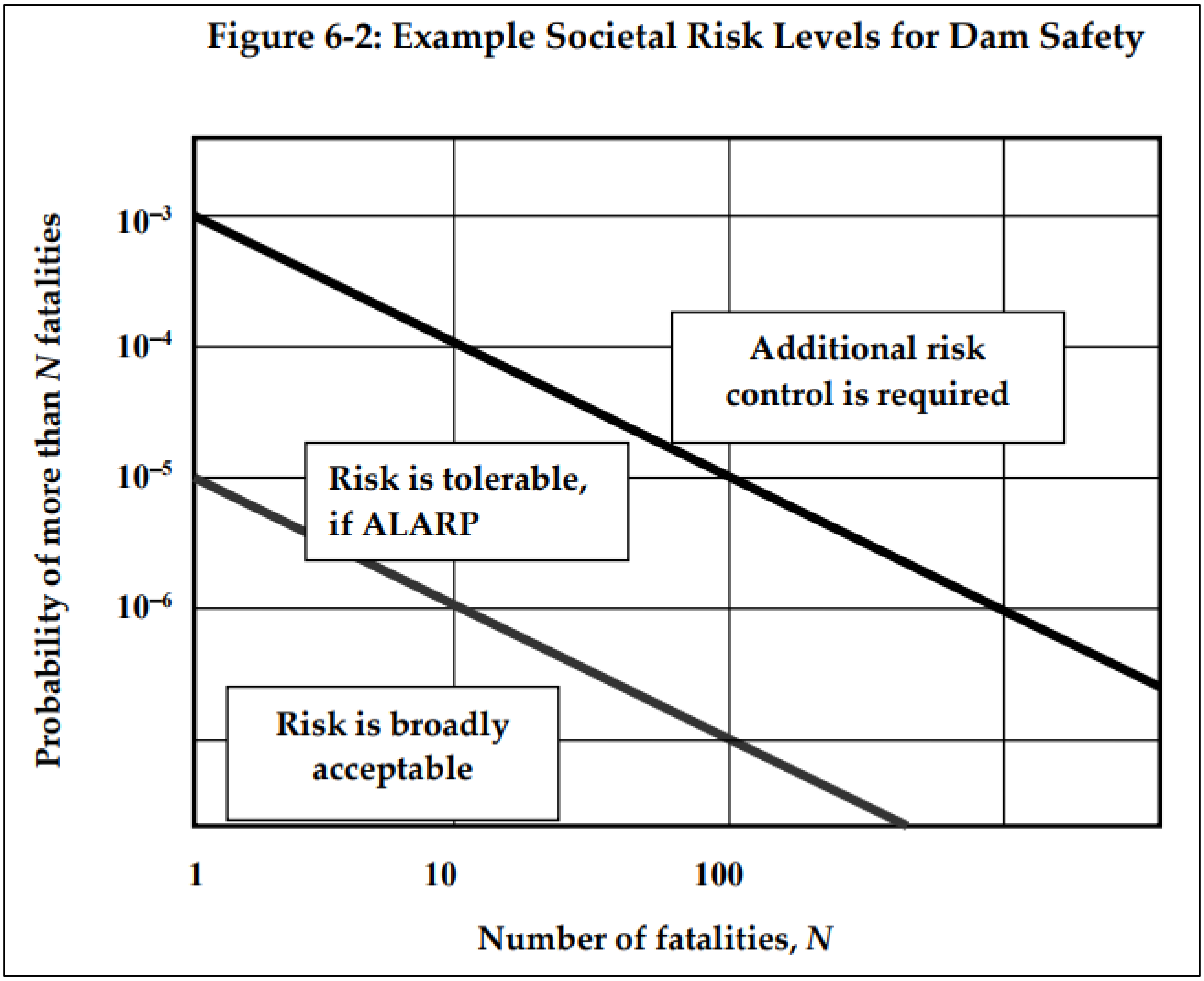


Figure 35a. According to the guidelines of the Canadian Dam Association, an annual probability of dam failure of 0.1% (1 in 1000) is marginally acceptable (outside of the region "Additional risk control is required") only if dam failure would result in no more than one potential fatality, and broad acceptability would require an annual probability of failure no greater than 0.001% (1 in 100,000). The dam failure consequence category of the tailings dams at the Copper Mountain mine is Extreme, meaning that failure would result in the potential loss of more than 100 lives. For the minimum of 100 fatalities, marginal acceptability would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while broad acceptability would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000). On the above basis, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) is entirely unacceptable. The region "Risk is tolerable, if ALARP" indicates that the risk is acceptable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to Canadian Dam Association (2013), "The ALARP principle is based on the duty to reduce risks to life to the point where further risk reduction is impracticable or requires action that is grossly disproportionate in time, trouble, and effort to the reduction of risk achieved." Figure from Canadian Dam Association (2013).

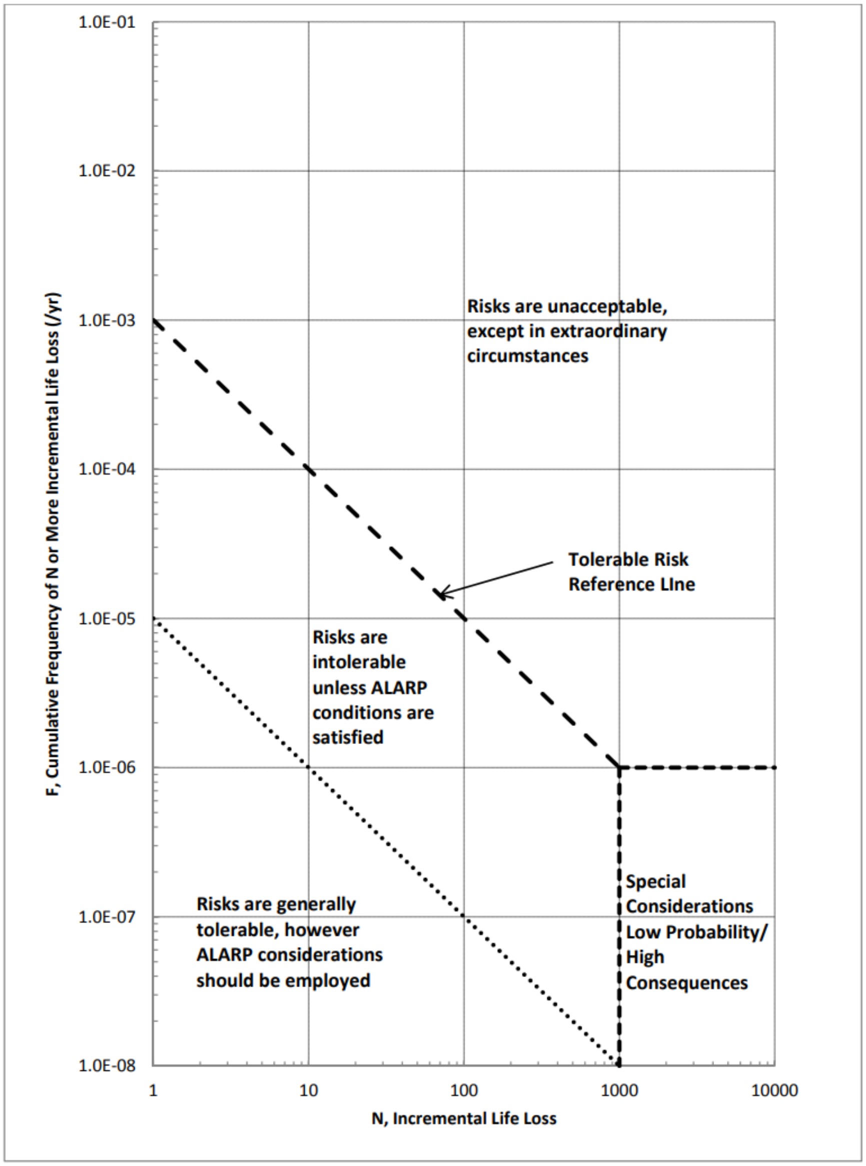
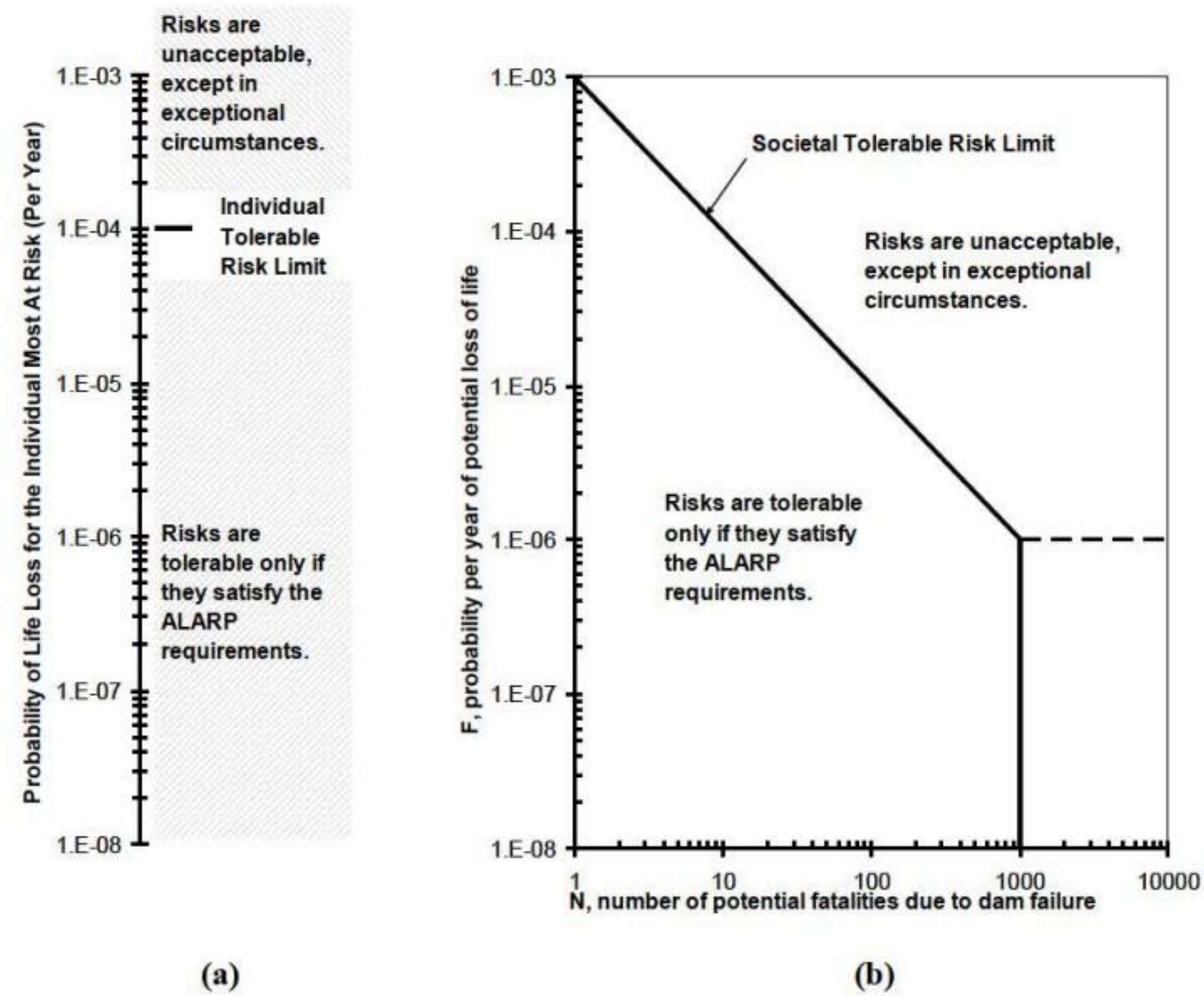


Figure 3-3. Societal Risk Guideline for Incremental Risk (F-N)

Figure 35b. According to the societal risk guidelines of the (USA) Federal Energy Regulatory Commission, an annual probability of dam failure of 0.1% (1 in 1000) is at the Tolerable Risk Reference Line (outside of the region “Risks are unacceptable, except in extraordinary circumstances”) only if dam failure would result in no more than one potential fatality, and the region “Risks are generally tolerable” would require an annual probability of failure no greater than 0.001% (1 in 100,000). The dam failure consequence category of the tailings dams at the Copper Mountain mine is Extreme, meaning that failure would result in the potential loss of more than 100 lives. For the minimum of 100 fatalities, the Tolerable Risk Reference Line would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while the region “Risks are generally tolerable” would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000). On the above basis, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) is entirely unacceptable. The region “Risk is intolerable, unless ALARP conditions are satisfied” indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to FERC (2016), “The application of ALARP considerations mean that actions should be taken to reduce risk below the tolerable risk reference line until such actions are impracticable or not cost effective.” Figure from FERC (2016).



Figures 5.4.a – Individual Risk Guidelines for Existing Dams
and 5.4.b – Societal Risk Guidelines for Existing Dams

Figure 35c. According to the societal risk guidelines of the U.S. Army Corps of Engineers for existing dams, an annual probability of dam failure of 0.1% (1 in 1000) is at the Societal Tolerable Risk Limit (outside of the region "Risks are unacceptable, except in extraordinary circumstances") only if dam failure would result in no more than one potential fatality. The dam failure consequence category of the tailings dams at the Copper Mountain mine is Extreme, meaning that failure would result in the potential loss of more than 100 lives. For the minimum of 100 fatalities, the Societal Tolerable Risk Limit would require annual probability of dam failure no greater than 0.001% (1 in 100,000). On the above basis, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) is entirely unacceptable. The region "Risks are tolerable only if they satisfy ALARP requirements" indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to USACE (2014), "The application of ALARP considerations mean that actions should be taken to reduce risk below the tolerable risk limit until such actions are impracticable or not cost effective." Figure from USACE (2014).

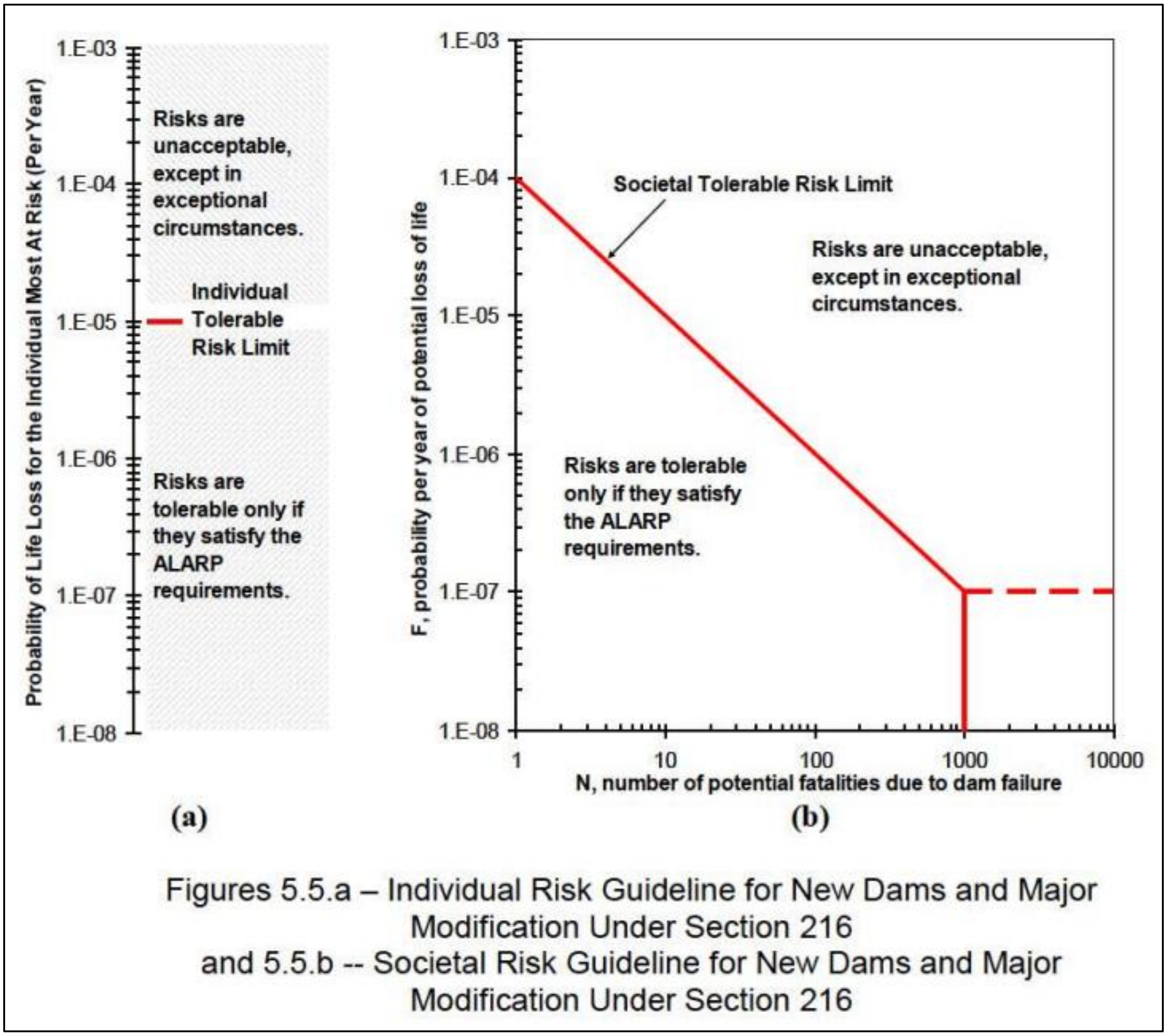


Figure 35d. According to the societal risk guidelines of the U.S. Army Corps of Engineers for new dams and major modifications, an annual probability of dam failure of 0.01% (1 in 10,000) is at the Societal Tolerable Risk Limit (outside of the region "Risks are unacceptable, except in extraordinary circumstances") only if dam failure would result in no more than one potential fatality. The dam failure consequence category of the tailings dams at the Copper Mountain mine is Extreme, meaning that failure would result in the potential loss of more than 100 lives. For the minimum of 100 fatalities, the Societal Tolerable Risk Limit would require annual probability of dam failure no greater than 0.0001% (1 in 1,000,000). On the above basis, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) is entirely unacceptable. The region "Risks are tolerable only if they satisfy ALARP requirements" indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to USACE (2014), "The application of ALARP considerations mean that actions should be taken to reduce risk below the tolerable risk limit until such actions are impracticable or not cost effective." Figure from USACE (2014).

Dam safety guidelines in the USA are based on similar probabilities, but with somewhat different language. Thus, an annual probability of failure of the Copper Mountain Tailings Management Facility in the range 0.1-1% (1 in 1000 to 1 in 100) would also be entirely unacceptable in the USA. According to the societal risk guidelines of the (USA) Federal Energy

Regulatory Commission (FERC, 2016), an annual probability of dam failure of 0.1% (1 in 1000) is at the Tolerable Risk Reference Line (outside of the region “Risks are unacceptable, except in extraordinary circumstances”) only if dam failure would result in no more than one potential fatality, and the region “Risks are generally tolerable” would require an annual probability of failure no greater than 0.001% (1 in 100,000) (see Fig. 35b). For the minimum of 100 fatalities (corresponding to the minimum potential loss of life in the event of failure of the tailings dams at the Copper Mountain mine), the Tolerable Risk Reference Line would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while the region “Risks are generally tolerable” would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000) (see Fig. 35b). As with the guidelines of the Canadian Dam Association (2013), the region “Risk is intolerable, unless ALARP conditions are satisfied” (FERC, 2016; see Fig. 35b) indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to FERC (2016), “The application of ALARP considerations mean that actions should be taken to reduce risk below the tolerable risk reference line until such actions are impracticable or not cost effective.”

The guidelines of the U.S. Army Corps of Engineers for existing dams (USACE, 2016) are similar to those of FERC (2016), except that there is no lower bound on the annual probability of failure below which “risks are generally tolerable” (FERC, 2016) (see Figs. 35b-c). According to the societal risk guidelines of the U.S. Army Corps of Engineers for existing dams, an annual probability of dam failure of 0.1% (1 in 1000) is at the Societal Tolerable Risk Limit (outside of the region “Risks are unacceptable, except in extraordinary circumstances”) only if dam failure would result in no more than one potential fatality (see Fig. 35c). For the minimum of 100 fatalities, the Societal Tolerable Risk Limit would require annual probability of dam failure no greater than 0.001% (1 in 100,000). “Risks are tolerable only if they satisfy ALARP requirements” (see Fig. 35c) indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP). According to USACE (2014), “The application of ALARP considerations mean that actions should be taken to reduce risk below the tolerable risk limit until such actions are impracticable or not cost effective.”

The guidelines of the U.S. Army Corps of Engineers for new dams or dams undergoing major modifications (USACE, 2016) are still more conservative by an order of magnitude (see Fig. 35d). According to the societal risk guidelines of the U.S. Army Corps of Engineers for new dams and major modifications, an annual probability of dam failure of 0.01% (1 in 10,000) is at the Societal Tolerable Risk Limit (outside of the region “Risks are unacceptable, except in extraordinary circumstances”) only if dam failure would result in no more than one potential fatality (see Fig. 35d). For the minimum of 100 fatalities, the Societal Tolerable Risk Limit would require annual probability of dam failure no greater than 0.0001% (1 in 1,000,000). As with the minimum requirements for existing dams, the region “Risks are tolerable only if they satisfy ALARP requirements” (see Fig. 35d) indicates that the risk is tolerable only after all measures have been carried out to bring the annual probability of failure As Low as Reasonably Practicable (ALARP).

There is another perspective for explaining the unacceptability of annual probabilities of failure of tailings dams in the range 0.1-1% (1 in 1000 to 1 in 100). According to the SME (Society for Mining, Metallurgy and Exploration) <u>Tailings Management Handbook: A Life-Cycle Approach</u>, the qualitative equivalent for this probability range is that failure is “possible”

(Morrison and Byler, 2022). The corresponding description is "direct evidence or substantial indirect evidence exists to suggest that failure has initiated or is likely to occur" (Morrison and Byler, 2022). In other words, such a high annual probability of failure implies that failure is not simply a theoretical possibility, but that the sequence of events that would ultimately lead to failure has already been set into motion.

Significance of Reliance on Upstream Construction Method

It is now appropriate to consider the additional risk posed by the use of the upstream construction method for the tailings dams at the Copper Mountain mine. The failure of the upstream tailings dam near Brumadinho, Brazil, on January 25, 2019, which resulted in nearly 300 deaths (Robertson et al., 2019), was a watershed moment in the global awareness of the danger of the upstream construction method. However, in the five decades preceding the Brumadinho disaster, there were already numerous cautions and prohibitions regarding the use of the upstream method in guidance documents and regulations. The subject is discussed in some detail, since this material is not generally available in a single location.

Based upon the engineering principles discussed in the section Review of Tailings Dams Construction and the historical record at the time, the U.S. Environmental Protection Agency (USEPA, 1994) concluded that "A tailings pond that is expected to receive high rates of water accumulation (due to climatic and topographic conditions) should be constructed using a method other than upstream construction … upstream construction is not appropriate in areas with a potential for high seismic activity." The International Commission on Large Dams (ICOLD) and the United Nations Environment Programme (UNEP) came to the same conclusion in writing, "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 … 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 and UNEP, 2001). The recommendation to UNEP in 2017 was to "adopt a presumption against the use of … upstream and cascading tailings dams unless justified by independent review" (Roche at al., 2017). Finally, the European Commission concurred in writing, "The main disadvantage of the upstream method is the risk of physical instability of the dam and its susceptibility to liquefaction … In general, downstream dams are much safer than those built using the upstream method, particularly when subject to seismic loads … [Upstream dams are] not applicable when the slightest risk of liquefaction has been identified after seismic evaluation … Upstream: this option has the highest risk associated to dam wall breaking" (Garbarino et al., 2018).

Even before the Brumadinho disaster, the upstream construction method for tailings dams was prohibited under all circumstances in Chile and Peru (Ministerio de Minería (Chile) [Ministry of Mining (Chile)], 2007; Sistema Nacional de Información Ambiental (Perú) [National System of Environmental Information (Peru)], 2014). The prohibition against upstream dams in Chile has been in place for over 50 years (since 1970) and was motivated by the major earthquake in 1965 that caused the failure of 17 tailings dams, 16 of which had been constructed using the upstream method (Villavicencio et al., 2013; Valenzuela, 2016). The same pattern was repeated in the major earthquake in 1997, in which four tailings dams failed, three of which had been constructed using the upstream method and one of which combined upstream and centerline raises. By contrast, Chile has 757 tailings dams, including 465 tailings dams for which the method of construction is known. Out of the dams with a known construction method, 213 (46%) were constructed using the upstream method, all of which are now closed (SNGM, 2020).

Again long before the Brumadinho disaster, the upstream construction method was thoroughly critiqued in the two available textbooks on tailings dams. The first textbook was Planning, Design, and Analysis of Tailings Dams (Vick, 1990), which was first published in 1983 and reprinted without revision in 1990. According to Vick (1990), "Use of the upstream raising method, however, is limited to very specific conditions and incorporates a number of inherent disadvantages. Factors that constrain the application of the upstream method include phreatic surface [water table] control, water storage capacity, and seismic liquefaction susceptibility. The location of the phreatic surface is a critical element in determining embankment stability. For upstream embankments constructed by tailings spigotting, there are few structural measures for control of the phreatic surface within the embankment … Many if not most failures of upstream embankments can be attributed to inadequate separation distance between the decant pond and the embankment crest … For this reason, upstream embankments are poorly suited to conditions where water accumulation is anticipated due to flooding, long-term accumulation of seasonal runoff, or high rates of mill water accumulation. In general, upstream embankments cannot be used for water retention … The susceptibility of upstream embankments to liquefaction under severe seismic ground motion is well documented (Dobry and Alvarez, 1967). The low relative density and generally high saturation within the tailings deposit can result in liquefaction-induced flow of the tailings, with disastrous consequences. Upstream raising methods are clearly inappropriate in areas of high seismic potential … Upstream embankments, while providing the simplest and least costly raising method, are subject to a number of very critical constraints. Proper use of the method can be justified only when these constraints are thoroughly investigated and satisfied … The fact that so many variables cannot be controlled or easily predicted in advance of operation cannot help but inspire a certain feeling of helplessness among those who would attempt to predict the phreatic surface location within upstream embankments. This uneasiness is often manifested by a preference for other embankment types whose seepage and stability characteristics are more easily predicted and controlled." It should be noted that the susceptibility of upstream dams to failure due to seismic liquefaction had already been established by the mid-1960s (Dobry and Alvarez, 1967) and was the basis for the prohibition against upstream dams in Chile in 1970. The second textbook was Geotechnical Engineering for Mine Waste Storage Facilities (Blight, 2010), which was published 20 years after Vick (1990). Blight (2010) believed that upstream dams were already disappearing and wrote, "This particular method of construction is no longer used in many parts of the world, although it is still used in areas having an arid climate and no seismicity."

Following the Brumadinho disaster, two additional countries prohibited the use of the upstream construction method (ANM, 2019; Ministerio de Energía y Recursos Naturales No Renovables [Ministry of Energy and Non Renewable Natural Resources] (Ecuador), 2020), so that upstream dams are now prohibited in the four Latin American countries of Brazil, Chile, Ecuador and Peru. Ecuador went further than the other countries in preferring the downstream method and permitting the centerline method only under special circumstances. According to Ministerio de Energía y Recursos Naturales No Renovables (2020), "Se prohíbe la utilización del método hacia aguas arriba. De manera estandarizada el método de construcción será hacia aguas abajo, incluyendo la presa de arranque. El método de construcción de eje central se aprobará en los casos en que la morfología o espacio del terreno no permitan el crecimiento hacia aguas abajo, siempre y cuando se cumpla con condiciones favorables para la estabilidad física del depósito de relaves" [The use of the upstream method is prohibited. In a standardized way, the construction method will be downstream, including the starter dike. The centerline construction method will be approved in cases where the morphology or space of the land does not allow for downstream growth, only and when it meets favorable conditions for the physical stability of the tailings deposit]. Brazil also required the safe closure of existing upstream tailings dams storing less than 12 million cubic meters of tailings, 12-30 million cubic meters of tailings, and greater than 30 million cubic meters of tailings by September 2022, September 2025, and September 2027, respectively (ANM, 2019).

Some post-Brumadinho guidance documents reinforced previous cautions regarding upstream tailings dams, but did not explicitly call for a prohibition on the upstream construction method. According to Canadian Dam Association (2019), "It is recommended that upstream constructed tailings dams not be built in high seismic areas." According to ICOLD (2021), "ICOLD Bulletin B 121 [ICOLD and UNEP, 2001] discusses a key risk inherent in upstream construction being the potential for tailings in the structural zone to remain saturated at low density, resulting in tailings being in a contractive state, susceptible to static or dynamic liquefaction … The stability of the upstream slope is dependent upon the strength of the impounded tailings [as opposed to dependence only upon the strength of the dikes], which form part of the upstream section … The extent of saturation is sometimes difficult to determine with perched water tables being common due to segregation and layering. Piezometers cannot be relied on to give an accurate picture of the phreatic surface, particularly if vertical drainage is occurring and/or perched water tables are present. Caution should be applied when considering upstream construction, particularly when using fine tailings that have poor drainage characteristics and in climates where drying effects might be limited and/or in areas of moderate seismicity." Finally, the SME (Society for Mining, Metallurgy and Exploration) Tailings Management Handbook: A Life-Cycle Approach reinforced earlier critiques of the upstream method and even the centerline method in writing, "Upstream construction, and to a lesser degree centerline construction, with the placement of the embankment crest raising on tailings, introduces stability concerns because of the potentially low strength of the saturated tailings during initial covering and the potential for seismically induced strength degradation … Instability and earthquake-related incidents have generally been predominant at upstream and centerline facilities … [The upstream method is] typically more susceptible to instability particularly under earthquake loading" (Snow, 2022).

On the other hand, Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2022) followed the regulations in the four Latin American countries and did call for a prohibition on new upstream tailings dams and the safe closure of existing upstream dams. According to Morrill et al. (2022), "Because of the demonstrated risk associated with upstream dam construction, upstream dams must not be built at any new facilities. Upstream construction is especially problematic in areas with moderate or high seismic risk, or in wet climate areas with net precipitation (more precipitation than evaporation), especially as weather events become increasingly severe with climate change … Expansion of existing upstream tailings facilities must cease, and these facilities must be safely closed as soon as possible. This includes dams where companies have been approved for permits that have not begun or are just beginning construction. The deadline for safe closure must depend on engineering and the safety of affected communities, rather than economic considerations."

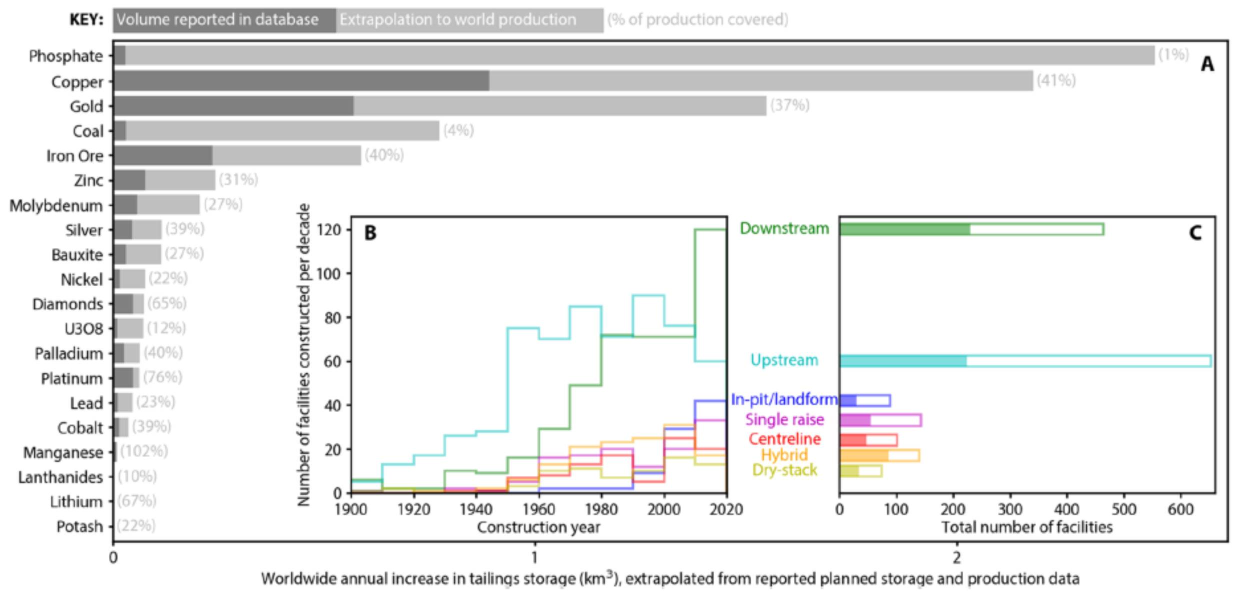


Figure 1. Tailings storage. (**A**) Tailings storage volume increase per year over the 2019–2023 period for a range of commodities as reported in the dataset and extrapolated to world production. (**B**) Number of reported facilities constructed per decade by raise type. (**C**) Reported tailings facilities by raise type. Shading indicates active facilities.

Figure 36. According to Franks et al. (2021), "while upstream facilities make up 37 per cent of the total, they have declined from a peak of 85 per cent of new facilities in 1920–1929 to 19 per cent of new facilities in 2010–2019 (Fig. 1B)." In addition, upstream facilities made up 45%, 41%, and 32% of total new facilities for the decades 1960-1969, 1970-1979, and 1980-1989, respectively, indicating that it was generally known by the 1970s that the benefits of upstream construction did not outweigh the risks. Figure from Franks et al. (2021).

One of the most significant post-Brumadinho developments has been the development of the Global Tailings Portal (GRID-Arendal, 2022) and its analysis by Franks et al. (2021). For the first time, this analysis quantified the greater risk posed by upstream dams and the gradual disappearance of the upstream construction method for new tailings storage facilities. According to Franks et al. (2021), "Controversy has surrounded the safety of tailings facilities, most notably upstream facilities, for many years but in the absence of definitive empirical data differentiating the risks of different facility types, upstream facilities have continued to be used widely by the industry and a consensus has emerged that upstream facilities can theoretically be built safely under the right circumstances." Franks et al. (2021) showed that the retreat from the upstream construction method was well underway, even by the 1970s (see Fig. 36). According to Franks et al. (2021), "While upstream facilities make up 37 per cent of the total, they have declined from a peak of 85 per cent of new facilities in 1920–1929 to 19 per cent of new facilities in 2010–2019" (see Fig. 36). In addition, upstream facilities made up 45%, 41%, and 32% of total new facilities for the decades 1960-1969, 1970-1979, and 1980-1989, respectively, indicating that it was generally known even in those decades that the benefits of upstream construction did not outweigh the risks. According to Franks et al. (2021), "Owing to their historical popularity, upstream facilities make up 43 per cent of facilities that are inactive, closed or reclaimed. However, in the past twenty years, the number of new downstream and in-pit/natural landform facilities have risen sharply … At present, the number of active downstream facilities (230) marginally exceeds the number of active upstream facilities (224)" (see Fig. 36). At the present time, "Upstream facilities represent a relatively low number of active facilities in North and

South America when compared to Africa and Oceania" (Franks et al., 2021). The conclusions by Franks et al. (2021) reinforced the general impression by Blight (2010) and the earlier statement by USEPA (1994) that "most recent dike dams have been built using downstream or centerline methods rather than the upstream method" (USEPA, 1994).

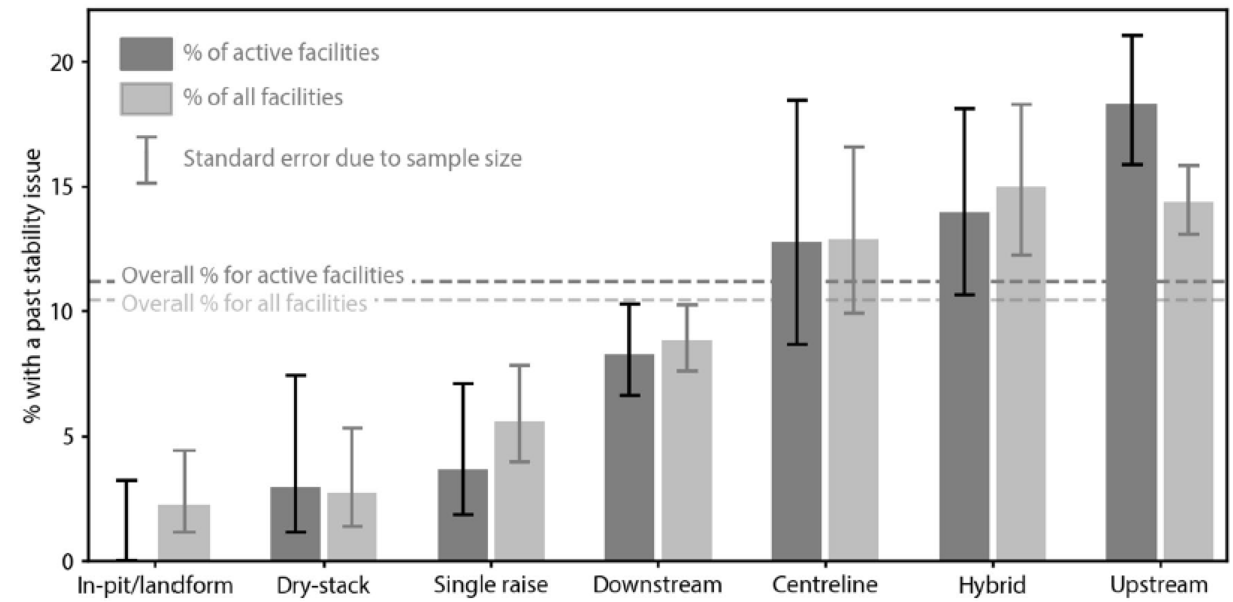


Figure 3. Stability of tailings facilities. Proportion of facilities with a stability issue by raise type. Error bar lengths are binomial confidence intervals for the subsample represented by each bar, showing ± 1 standard error (approximately 68%).

Figure 37. According to Franks et al. (2021), "Our findings reveal that in practice active upstream facilities report a higher incidence of stability issues (18.3%) than other facility types, and that this elevated risk persists even when these facilities are built in high governance settings … The likelihood of a stability issue in active upstream facilities is twice that of active downstream facilities … The control tests [age, height, volume, seismic hazard, wind speed, and rainfall] showed that the properties of the upstream samples (notably their distribution of age), have a small effect on the incidence of stability, however the estimated effect is only about one standard error, and is not sufficient to account for their higher than average incidence." The stability issue was an answer to the particular question "Has this facility, at any point in its history, failed to be confirmed or certified as stable, or experienced notable stability concerns, as identified by an independent engineer (even if later certified as stable by the same or a different firm)?" with the clarification "We note that this will depend on factors including local legislation that are not necessarily tied to best practice. As such, and because remedial action may have been taken, a 'Yes' answer may not indicate heightened risk. Stability concerns might include toe seepage, dam movement, overtopping, spillway failure, piping etc. If yes, have appropriately designed and reviewed mitigation actions been implemented? We also note that this question does not bear upon the appropriateness of the criteria, but rather the stewardship levels of the facility or the dam" (Franks et al., 2021). Figure from Franks et al. (2021).

Among other information, the Global Tailings Portal includes the history of stability concerns. The history of stability concerns is a yes or no answer to the question "Has this facility, at any point in its history, failed to be confirmed or certified as stable, or experienced notable stability concerns, as identified by an independent engineer (even if later certified as stable by the same or a different firm)? (GRID-Arendal, 2022) with the clarification "We note that this will depend on factors including local legislation that are not necessarily tied to best practice. As such, and because remedial action may have been taken, a 'Yes' answer may not indicate heightened risk. Stability concerns might include toe seepage, dam movement, overtopping, spillway failure, piping etc. If yes, have appropriately designed and reviewed mitigation actions been implemented? We also note that this question does not bear upon the appropriateness of the criteria, but rather the stewardship levels of the facility or the dam" (GRID-Arendal, 2022). Franks et al. (2021) used these responses to establish that upstream dams have increased stability issues, even in cases where the stability issues did not proceed to dam failure (see Fig. 37). According to Franks et al. (2021), "Our findings reveal that in practice active upstream facilities report a higher incidence of stability issues (18.3%) than other facility types, and that this elevated risk persists even when these facilities are built in high governance settings … The likelihood of a stability issue in active upstream facilities is twice that of active downstream facilities … The control tests [age, height, volume, seismic hazard, wind speed, and rainfall] showed that the properties of the upstream samples (notably their distribution of age), have a small effect on the incidence of stability, however the estimated effect is only about one standard error, and is not sufficient to account for their higher than average incidence."

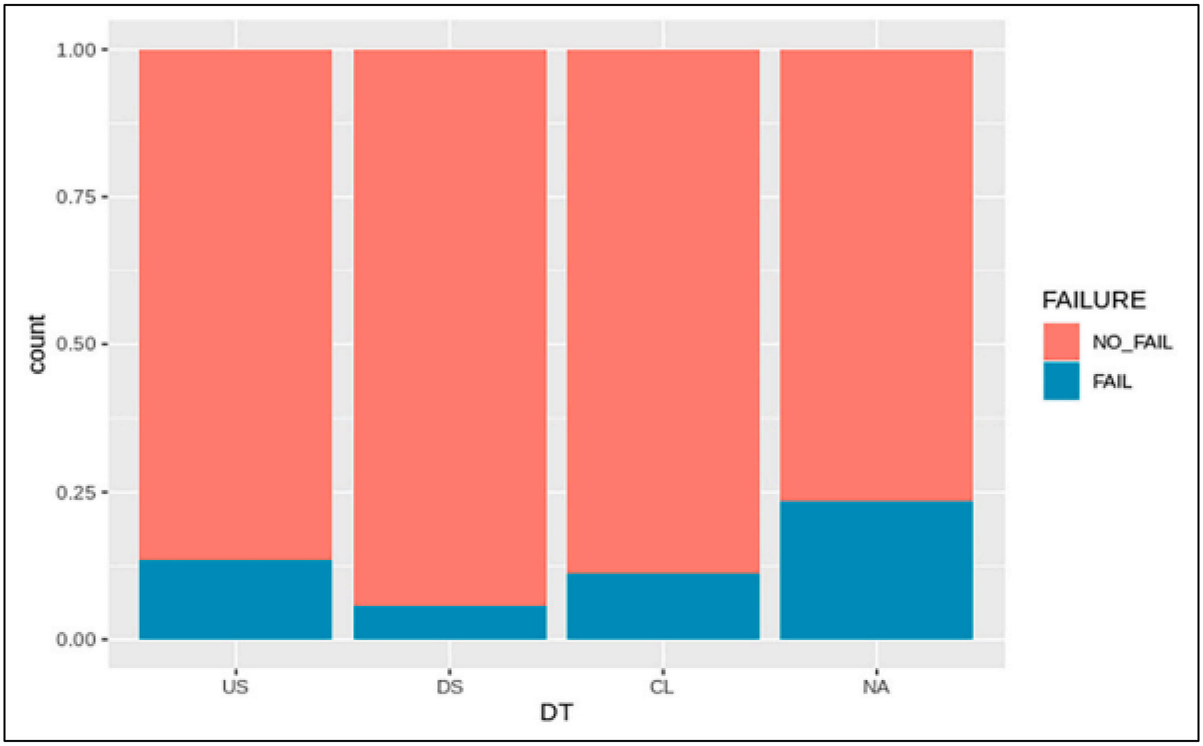


Figure 38. By comparing datasets on global tailings dam failures (Center for Science in Public Participation, 2022) with global tailings dams (Franks et al., 2021; GRID-Arendal, 2022), Piciullo et al. (2022) showed a disproportionately large representation of upstream tailings dams among tailings dam failures. DT = Dam Type, US = Upstream, DS = Downstream, CL = Centerline. Figure from Piciullo et al. (2022).

In addition to greater stability issues, Piciullo et al. (2022) have documented the disproportionately large representation of upstream tailings dams among tailings dam failures (see Fig. 38). According to Piciullo et al. (2022), "Joining the databases on failures and existing dams, the fraction of failures as a function of the dam construction method has been computed … we observe that for a relatively high fraction of the incidents in the failure database the construction method was not known … For the tailings dam failures with a documented construction method, a higher frequency (relative to total number of dams in the catalogue of tailings dams) is observed for the upstream method (0.13), followed by the centreline construction method (0.11) and the downstream construction method (0.07) … An analysis with the failure database only … suggests that the downstream method is second in term of number of failures … The analysis presented in Fig. 13 [Fig. 38 in this report], using failure and nonfailure databases, shows that the frequency of failures is lower for the downstream method compared to the centreline. This result agrees with the survey carried out by Franks et al., 2021, who highlighted that active upstream facilities show a higher incidence of stability issues than other construction methods." In principle, a diagram such as Fig. 38 could be used to adjust annual probabilities of failure for tailings dams based on historical data to achieve a higher annual probability of failure for upstream dams, such as the tailings dams at the Copper Mountain mine. This has not been done in this report and would not affect the conclusions.

Set against all of the preceding cautions and prohibitions has been a persistent apology in the mining literature that upstream tailings dams can be safe if they are constructed and operated under ideal conditions (low seismicity and precipitation) and by high-quality personnel who do not make mistakes. The classic paper in this literature is Martin et al. (2002) who wrote "Upstream dams are not necessarily inherently unstable and dangerous. They can be as safe as other types of dams provided site conditions are favorable and that the rules for their safe design, construction and operation are followed … Conventional upstream dams cannot be considered for areas of moderate to high seismicity. Improved upstream construction, involving a combination of compaction of the outer shell and good internal drainage, can be used in such areas." Martin et al. (2002) then presented ten rules for the safe construction of upstream dams with the warning, "Of the 10 rules, a 'score' of 9/10 will not necessarily have a better outcome than 2/10, *as any omission* creates immediate candidacy for an upstream tailings dam to join the list of facilities that have failed due to ignoring some or all of the rules" (emphasis added by Hopkins and Kemp (2021)).

Hopkins and Kemp (2021) reacted to the warning by Martin et al. (2002) by writing, "This is a slightly obscure statement that may need to be read twice to reveal its true meaning." (The interpretation by the author is that, from the perspective of Hopkins and Kemp (2021), Martin et al. (2002) described upstream dam construction as if it were a kind of ice climbing expedition in which everything would be fine as long as no mistakes were made.) Morrill et al. (2022) further advanced the critique by writing, "It is theoretically possible to safely construct and operate an upstream tailings dam under the limited conditions of low seismicity, low precipitation and highly-trained personnel. Even under those limited conditions, a very influential tailings industry paper, with many antecedents, has argued that there are ten rules for upstream dams and not a single one can be violated without substantial risk of failure. There is broad consensus within the engineering community, especially in high-risk industries such as aviation and pipelines, that engineered structures should be robust, with multiple back-ups and defense mechanisms. The need to obey ten rules with no margin for error does not constitute a basis for safe design."

The apology for the upstream construction method has not abated even after the Brumadinho disaster. In the introductory presentation to a short course entitled "What is Brittle Tailings Behavior, How is it Characterized, and Why is it Important to Understand?" in February 2022, Winkler (2022), wrote, "Upstream dams: • are not inherently unsafe, • nor do they inherently pose unacceptable risk … • Highest risk means there are many things that have to be done right: corollary is that only a few things need to go wrong to create problems • This method of construction is generally less robust than others – this must be mitigated by application of the appropriate standard of care to achieve conditions aligned with the 'good practice' condition … • The relative simplicity of their construction and operation does not reflect the geotechnical complexity of these structures • This complexity demands a high standard of care in design, construction, operation, monitoring, and ongoing evaluation/review."

The point is not to repeat yet one more call for a prohibition on upstream tailings dams, but to emphasize that nearly all apologists for upstream dams have essentially said that the construction method is safe only with the highest Level of Engineering. On that basis, a Level of Engineering in the category Average to Above Average is entirely unacceptable for upstream dams, such as the tailings dams at the Copper Mountain mine. Even if upstream dams were not prohibited, no Level of Engineering lower than the category Best would be acceptable for upstream tailings dams under any circumstances. The warning by Silva et al. (2010) is now repeated for the third time: "Then there are those [engineering projects] requiring 'best' practices where the consequences of poor performance are very large … These are projects like … major dams."

Long-Term Prospects for Tailings Dams at Copper Mountain Mine

At the present time there is a proposal to raise the permitted elevation for the Copper Mountain Tailings Management Facility to 1060 meters above sea level after the currently permitted elevation of 997 meters above sea level has been achieved in 2027 (Copper Mountain Mining Corporation, 2020; Klohn Crippen Berger, 2020a). It should go without saying that no such proposal, and even no further dam raising, should be entertained until the annual probability of failure of the tailings dams can be reduced to no greater than 0.001% (1 in 100,000), and even lower as required by ALARP principles. In accordance with the guidelines of the Canadian Dam Association (2013), an annual probability of failure of 0.001% is the absolute maximum that would be tolerable for a potential loss of 100 lives in the event of dam failure (see Fig. 35a). Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2022) reached the same conclusion, but without connection to a particular number of lives. According to Morrill et al. (2022), "For tailings dams where failure would result in the potential loss of human life, an acceptable annual probability of failure must be no greater than 0.001%."

It is further recommended that the regulatory agencies in British Columbia move forward from their current narrow focus on the factor of safety and consider the annual probability of failure, which is a standard practice in the dam industry in Canada and the USA. In particular, the regulatory agencies should take into explicit consideration the quality of the input data that went into the calculation of the factor of safety and the level of engineering that accompanies a given factor of safety. Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2022) has also called for a focus on annual probability of failure, in addition to factor of safety, as well as full transparency as to how annual probability of failure has been estimated. According to Morrill et al. (2022), "Although the FoS [Factor of Safety] is still included in many regulations and guidelines, it is a poor predictor of the annual probability of failure. In order to more accurately identify risk, dam designs and evaluations must consider the annual probability of failure, in addition to the FoS. Annual probabilities of failure have been relied upon in many industries, such as aviation and aerospace, since the Second World War … The annual probability of failure must be periodically calculated by the operating company. The annual probability of failure and the methodology used to reach it must be published both as a technical document, and as a document that affected communities can access and understand. Risk analysis used to calculate the annual probability of failure must consider more than just the maximum credible precipitation or seismic events."

Table 2a. Maximum possible future Level of Engineering (Design – Investigation) for tailings dams at Copper Mountain mine: ABOVE AVERAGE to BEST (0.3)[1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Evaluate design and performance of nearby structures	Evaluate design and performance of nearby structures	Evaluate performance of nearby structures	No field investigation
Analyze historic aerial photographs	Exploration program tailored to project conditions by qualified engineer	Estimate subsoil profile from existing data and borings	
Locate all nonuniformities (soft, wet, loose, high, or low permeability zones)			
Determine site geologic history			
Determine subsoil profile using continuous sampling			
Obtain undisturbed samples for lab testing of foundation soils			
Determine field pore pressures			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled or unknown, green = fulfilled

Table 2b. Maximum possible future Level of Engineering (Design – Testing) for tailings dams at Copper Mountain mine: ABOVE AVERAGE to BEST (0.3) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Run lab tests on undisturbed specimens at field conditions	Run standard lab tests on undisturbed specimens	Index tests on samples from site	No laboratory tests on samples obtained at the site
Run strength test along field effective and total stress paths	Measure pore pressure in strength tests		
Run index field tests (e.g., field vane, cone penetrometer) to detect all soft, wet, loose, high, or low permeability zones	Evaluate differences between laboratory test conditions and field conditions		
Calibrate equipment and sensors prior to testing program			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled or unknown, green = fulfilled

Table 2c. Maximum possible future Level of Engineering (Design – Analyses and Documentation) for tailings dams at Copper Mountain mine: ABOVE AVERAGE to BEST (0.3) [1,2,3]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Determine FS using effective stress parameters based on measured data (geometry, strength, pore pressure for site)	Determine FS using effective stress parameters and pore pressures	Rational analyses using parameters inferred from index tests	Approximate analyses using assumed parameters
Consider field stress path in stability determination	Adjust for significant differences between field stress paths and stress path implied in analysis that could affect design		
Prepare flow net for instrumented sections			
Predict pore pressure and other relevant performance parameters (e.g., stress, deformation, flow rates for instrumented section)			
Have design report clearly document parameters and analyses used for design			
No errors or omissions			
Peer review			

[1]Table adapted from Silva et al. (2008)
[2]FS = Factor of safety
[3]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

Table 2d. Maximum possible future Level of Engineering (Construction) for tailings dams at Copper Mountain mine: ABOVE AVERAGE (0.4) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Full time supervision by qualified engineer	Part-time supervision by qualified engineer	Informal construction supervision	No construction supervision by qualified engineer
Construction control tests by qualified engineers and technicians	No errors or omissions		No construction control tests
No errors or omissions			
Construction report clearly documents construction activities			

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

The obvious question at this point is: What would be the annual probability of failure of the Copper Mountain Tailings Management Facility if all design, construction, operation and monitoring were carried to the highest standards (Level of Engineering in the Best category) from now on? The important issues are the lack of sufficient characterization of the foundation before construction of the tailings facility, which, according to the 2021 Dam Safety Review (Tetra Tech, 2021), can no longer be fixed, as well as the lack of construction testing and quality control that occurred prior to 2015. Thus, no matter how the engineered was improved from now on, the following characteristics would remain as "partially fulfilled":

1) Analyze historic aerial photographs (Best, see Table 2a)
2) Locate all nonuniformities (soft, wet, loose, high, or low permeability zones) (Best, see Table 2a)
3) Determine site geologic history (Best, see Table 2a)
4) Determine subsoil profile using continuous sampling (Best, see Table 2a)
5) Obtain undisturbed samples for lab testing of foundation soils (Best, see Table 2a)
6) Run index field tests (e.g., field vane, cone penetrometer) to detect all soft, wet, loose, high, or low permeability zones (Best, see Table 2b)
7) Determine FS using effective stress parameters based on measured data (geometry, strength, pore pressure for site (Best, see Table 2c)
8) Determine FS using effective stress parameters and pore pressures (Above Average, see Table 2c)
9) Rational analyses using parameters inferred from index tests (Average, see Table 2c)
10) Approximate analyses using assumed parameters (Poor, see Table 2c)

11) Have design report clearly document parameters and analyses used for design (Best, see Table 2c)
12) No errors or omissions (Best, see Table 2c)
13) No errors or omissions (Best, see Table 2d)
14) No errors or omissions (Above Average, see Table 2d)
15) Construction control tests by qualified engineers and technicians (Best, see Table 2d)
16) Construction report clearly documents construction activities (Best, see Table 2d)

Table 2e. Maximum possible future Level of Engineering (Operation and Monitoring) for tailings dams at Copper Mountain mine: BEST (0.2) [1,2]

I (BEST) Facilities with high failure consequences (0.2)	II (ABOVE AVERAGE) Ordinary facilities (0.4)	III (AVERAGE) Unimportant or temporary facilities with low failure consequences (0.6)	IV (POOR) Little or no engineering (0.8)
Complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength, deformations)	Periodic inspection by qualified engineer	Annual inspection by qualified engineer	Occasional inspection by non-qualified person
No malfunctions (slides, cracks, artesian heads)	No uncorrected malfunctions	No field measurements	No field measurements
Continuous maintenance by trained crews	Selected field measurements	Maintenance limited to emergency repairs	
	Routine maintenance		

[1]Table adapted from Silva et al. (2008)
[2]Red = not fulfilled, yellow = partially fulfilled, green = fulfilled

In summary, the maximum future Levels of Engineering would be Above Average to Best (score = 0.3) in the area of Design – Investigation (see Table 2a), Above Average to Best (score = 0.3) in the area of Design – Testing (see Table 2b), Above Average to Best (score = 0.3) in the area of Design – Analyses and Documentation (see Table 2c), Above Average (score = 0.4) in the area of Construction (see Table 2d), and Best (score = 0.2) in the area of Operation and Monitoring. The overall score would be 1.5 or midway between Above Average and Best. There is no way to determine how the factors of safety might change if they were calculated using more accurate and complete input data. Assuming the calculated factors of safety of FS = 1.3 and FS = 1.4 would still be valid for the East Dam after improved engineering, the minimum future annual probability of failure of the East Dam was estimated in the range 0.007-0.049% with a best estimate of 0.018% (see Fig. 39a). Assuming the calculated factors of safety of FS = 1.3 and FS = 1.7 would still be valid for the West Dam after improved engineering, the minimum future annual probability of failure of the West Dam was estimated in the range 0.00005-0.007% with a best estimate of 0.002% (see Fig. 39b).

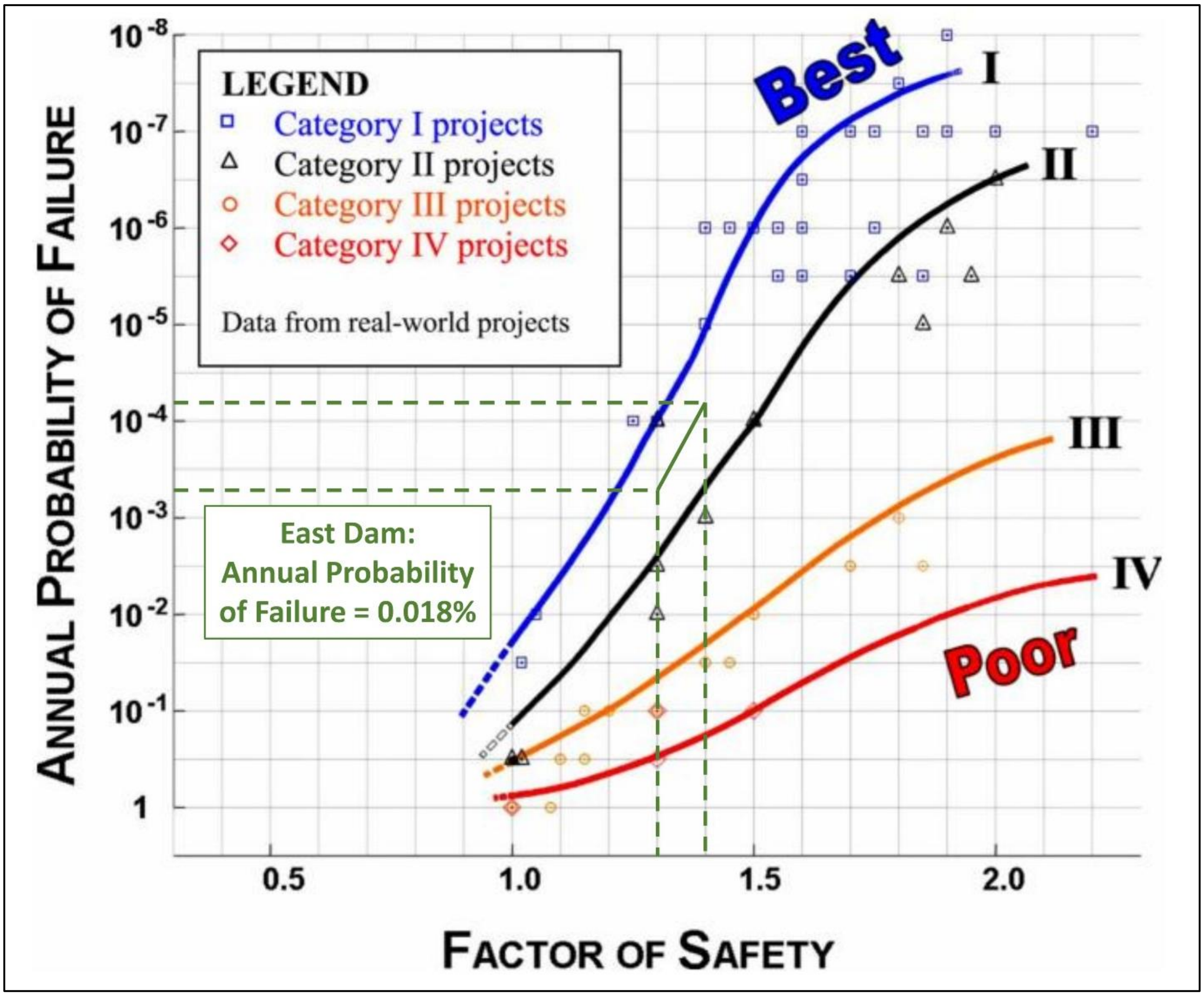


Figure 39a. If all engineering from now on were elevated to the highest standards, the Level of Engineering could be increased to 1.5 or midway between Above Average and Best (see Tables 2a-e). The maximum future Level of Engineering is constrained by the characteristics that cannot be fixed, such as the insufficient investigation of the foundation prior to constructing the tailings management facility (see Figs. 19a-b). Assuming the calculated factors of safety of FS = 1.3 and FS = 1.4 would still be valid after improved engineering (see Fig. 26a), the minimum future annual probability of failure of the East Dam was estimated in the range 0.007-0.049% with a best estimate of 0.018%. Based upon the best estimate for the minimum annual probability of failure of the West Dam as 0.002% (see Fig. 39b), the best estimate for the minimum annual probability of failure of the Copper Mountain Tailings Management Facility after improvement of engineering to the highest standards would be 0.02%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.01-0.1% (1 in 10,000 to 1 in 1000). Figure modified from Silva et al. (2008).

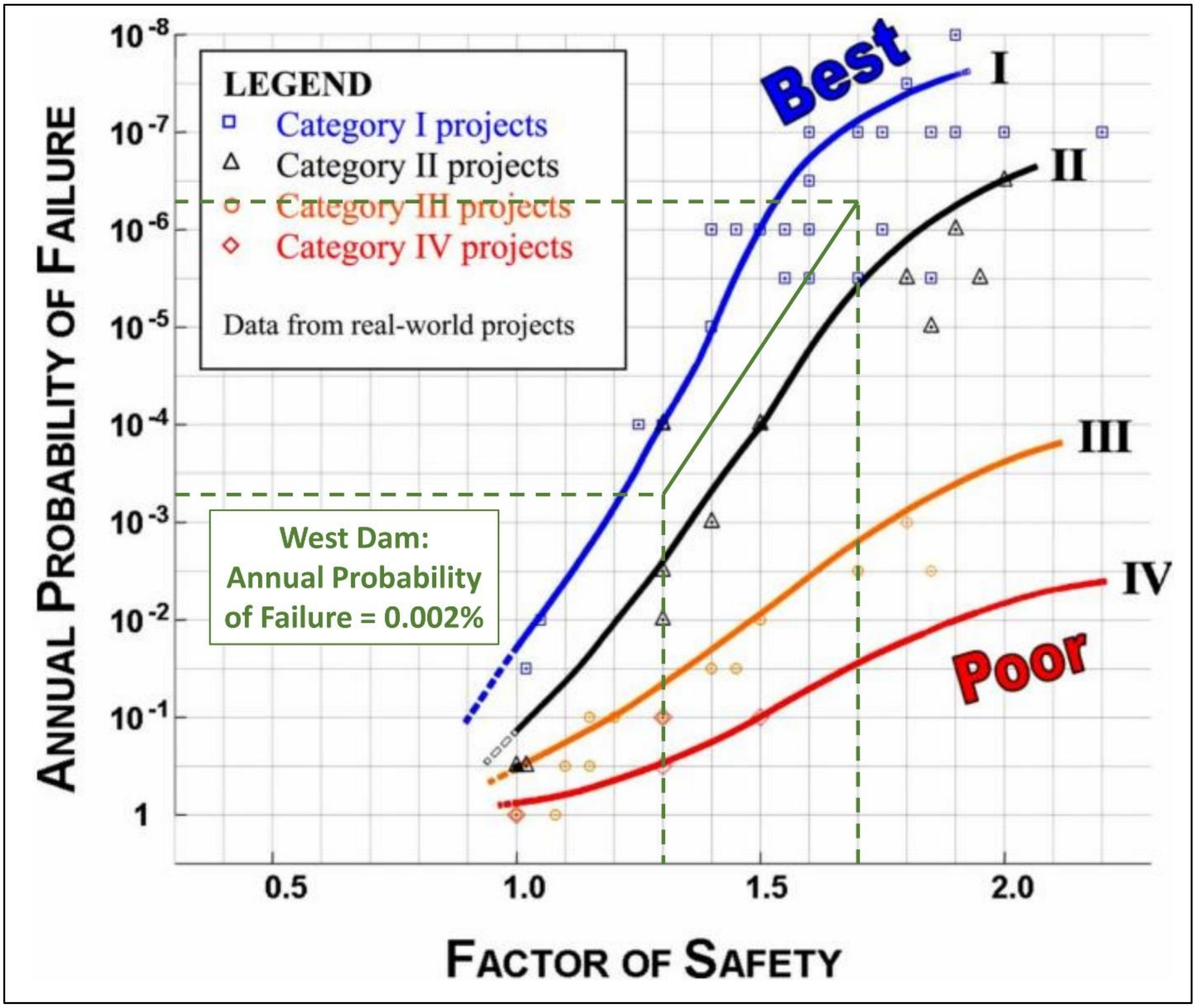


Figure 39b. If all engineering from now on were elevated to the highest standards, the Level of Engineering could be increased to 1.5 or midway between Above Average and Best (see Tables 2a-e). The maximum future Level of Engineering is constrained by the characteristics that cannot be fixed, such as the insufficient investigation of the foundation prior to constructing the tailings management facility (see Figs. 19a-b). Assuming the calculated factors of safety of FS = 1.3 and FS = 1.7 would still be valid after improved engineering (see Fig. 26b), the minimum future annual probability of failure of the West Dam was estimated in the range 0.00005-0.007% with a best estimate of 0.002%. Based upon the best estimate for the minimum annual probability of failure of the East Dam as 0.018% (see Fig. 39a), the best estimate for the minimum annual probability of failure of the Copper Mountain Tailings Management Facility after improvement of engineering to the highest standards would be 0.02%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.01-0.1% (1 in 10,000 to 1 in 1000). Figure modified from Silva et al. (2008).

Based upon the above best estimates for the East and West Dams, the best estimate for the minimum annual probability of failure of the Copper Mountain Tailings Management Facility after improvement of engineering to the highest standards would be 0.02%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.01-0.1% (1 in 10,000 to 1 in 1000). Thus, at most, improved engineering could reduce the annual probability of failure by one order of magnitude. An annual probability of failure in the range 0.01-1% is still at least an order of magnitude higher than the absolute maximum annual probability of failure of 0.001% (1 in 100,000) that would be tolerable for a potential loss of 100 lives in the event of dam failure, according to the guidelines of the Canadian Dam Association (2013) (see Fig. 35a). From another perspective, the description by Morrison and Byler (2022) for annual probabilities of failure in the range 0.01-0.1% (1 in 10,000 to 1 in 1000) is "The fundamental condition or defect [that could lead to tailings dam failure] is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward 'more likely' than 'less likely.'" It is in no way obvious how to achieve an adequate level of risk reduction and such considerations are beyond the scope of this report.

Although this report has focused on short-term risks (over years), the long-term risks (over centuries) should not be ignored. In the case of the Copper Mountain Tailings Management Facility, the short term refers to the period of active operation during which the facility is still receiving tailings. Since the currently permitted dam crest elevation of 997 meters above sea level will be achieved in 2027, this short term could end in as soon as five years. The long term refers to the centuries or millennia following closure of the facility. During this closure period, the tailings facility may or may not continue to be monitored, inspected and maintained. However, it is unlikely that the Copper Mountain Tailings Management Facility will be monitored, inspected, and maintained forever.

By comparison, at the end of its useful life, or when it is no longer possible to inspect and maintain the dam, a water-retention dam is completely dismantled. A water-retention dam cannot simply be abandoned or it will eventually fail at an unpredictable time with consequences that are difficult to predict. The same logic applies to any engineered structure, such as a building or a bridge. Either the structures are maintained or they must be demolished. They cannot simply be abandoned without any further maintenance, or they will undergo inevitable failure at an unpredictable time with consequences that are difficult to predict. However, the East and West Dams at the Copper Mountain Tailings Management Facility are expected to confine the tailings in perpetuity. Thus, the tailings dams can never be dismantled unless somehow the tailings can be moved to another location, such as an abandoned open pit.

Dr. Steven Vick, the author of the standard textbook Planning, Design, and Analysis of Tailings Dams (Vick, 1990) and one of the members of the expert panel that reviewed the tailings dam failure at the Mount Polley mine (Independent Expert Engineering Investigation and Review Panel, 2015a-b), has argued that the failure of a closed tailings dam is inevitable. Since it is inevitable, risk reduction must focus on reducing the consequences of failure, for example, by not constructing new tailings dams immediately upstream from communities. In a conference presentation, Vick (2014a) concluded that "System failure probabilities much less than 50/50 are unlikely to be achievable over performance periods greater than 100 years … system failure probability approaches 1.0 after several hundred years." Vick (2014a) continued, "For closure, system failure is inevitable … so closure risk depends solely on failure consequences." In the accompanying conference paper, Vick (2015b) elaborated, "Regardless of the return period selected for design events, the cumulative failure probability will approach 1.0 for typical numbers of failure modes and durations. This has major implications. For closure conditions, the likelihood component of risk becomes unimportant and only the consequence component matters … This counterintuitive result for closure differs so markedly from operating conditions that it bears repeating. In general, reducing failure likelihood during closure—through more stringent design criteria or otherwise—does not materially reduce risk, simply because there are too many opportunities for too many things to go wrong. In a statistical sense, all it can do is to push failure farther out in time. System failure must be accepted as inevitable, leaving reduction of failure consequences as the only effective strategy for risk reduction during closure."

CONCLUSIONS

The chief conclusions of this report can be summarized as follows:

1) A key theme running throughout the determination of the Level of Engineering of the Copper Mountain Tailings Management Facility is the distinction between the construction quality that began in 2015 and the earlier construction quality. Beginning in 2015, there have been detailed construction reports with comparisons between lab and field measurements, lab tests carried out on undisturbed specimens at field conditions, and extensive quality control. However, in Dam Safety Inspection reports, all of the above construction quality applies only to the construction (dam raise) that was carried out over the previous year, not to the tailings management facility as an entirety. By contrast, according to the 2021 Dam Safety Review, the construction material for the starter dam was "random," there is no information on the construction material prior to 1980, and the reactivation construction in 2011 did not follow the permitted design. Since the approximate heights of the East Dam and West Dam at the end of 2014 were 129.5 meters and 121.5 meters, respectively (75% and 74% of the present height), due consideration was given to the low quality of the earlier construction in the assignment of the tailings dams at the Copper Mountain mine to the appropriate Level of Engineering in this report.
2) According to the 2021 Dam Safety Review, there was limited investigation of the foundation upstream of the starter dams and, due to the thickness of the impounded tailings, it would be prohibitively expensive to advance this investigation at the present time. There has never been an evaluation of the design or performance of nearby structures nor an analysis of historic aerial photographs. The knowledge of the pore pressures in the foundation is hampered by a lack of piezometers that are still functioning. Based on the above, the category Above Average (score of 0.4) was chosen for Level of Engineering in the area Design – Investigation.
3) There has been little documentation of calibration of equipment or sensors prior to testing and the use of index field tests to detect non-uniformities has been limited. There is no indication that strength tests were carried out along field effective and total stress paths or that pore pressure was measured in strength tests. Based on the above, as well as the contrast between the testing carried out before 2015 and beginning in 2015, the category Average to Above Average (score of 0.5) was chosen for Level of Engineering in the area Design – Testing.
4) The only stability analyses that have been carried out for the permitted elevation calculated static factors of safety FS of FS = 1.3 and FS = 1.4 for the East Dam, which are less than the minimum value of FS = 1.5 required in British Columbia. The higher factor of safety (FS = 1.4) was based upon long-term dam behavior (after dissipation of excess pore pressure generated during construction), which is irrelevant for dams that are under continual construction.
5) The same analyses calculated static factors of safety for the West Dam of FS = 1.3 based on a two-dimensional model and FS = 1.7 for a three-dimensional model. According to the 2021 Dam Safety Review, the three-dimensional calculation did not properly take into account the actual width of the weak glaciolacustrine layer in the foundation. The stability

analysis for the West Dam did not state the assumptions that were made for the position of the water table.

6) Later stability analyses calculated static factors of safety of FS = 1.6 and FS = 1.9 (only for long-term behavior) for the East Dam and FS = 1.6 for the West Dam. The later analyses were not carried out for the permitted elevation, but only for the elevation as it existed in 2020. According to the 2021 Dam Safety Review, the later stability analyses assumed water tables that were much lower than the earlier analyses and much lower than were justified by the piezometric data.
7) None of the stability analyses have considered the high water table that could result from an extreme storm event, such as the Probable Maximum Flood.
8) All of the stability analyses have assumed a density of the cycloned sands that compose the dam raises that is higher than what has been measured, which could result in a factor of safety that is either too low or too high. In summary, many aspects of the calculations of factor of safety have been based upon questionable assumptions, as opposed to measured parameters.
9) There has been no consideration of the field stress path in the stability determinations nor any adjustment for differences between field stress paths and the stress paths implied in the stability analyses. There is no flow net (showing flow paths) for instrumented sections nor any predictions of pore pressures and other relevant performance parameters, such as stress deformation or flow rates at instrumented sections. Although there are numerous brief tables of design criteria, there is nothing that would be considered a detailed Design Basis Report. It is assumed that the Independent Tailings Review Board is providing peer review, although there are no records of their deliberations or recommendations.
10) Based on the above, with special emphasis on the lack of measured parameters used for calculation of the factor of safety, the category Average (score of 0.6) was chosen for Level of Engineering in the area Design – Analyses and Documentation.
11) The contrast between the quality of the construction before 2015 and beginning in 2015 was a key factor in choosing the category for Level of Engineering in the area Construction. The category Best would require full-time supervision of all construction by a qualified engineer. However, the Operations, Maintenance and Surveillance Manual clarifies that supervision by a qualified engineer occurs only for “critical” construction, and not for “routine” or “significant” construction. The category Above Average (score of 0.4) was chosen for Level of Engineering in the area Construction, which essentially splits the difference between the earlier and later construction.
12) The annual Dam Safety Inspection reports have documented the steady breakdown of the tailings dam instrumentation. The number of functional piezometers has varied between 37 and 46 and was at an all-time low at the end of 2021. The 2021 Dam Safety Review drew particular attention to the lack of functional piezometers and the difficulty that posed for the correct delineation of the water table for stability analyses. Out of seven inclinometers that had been installed since 2011, only one was functional at the end of 2021. The category Best would require no malfunctioning instruments, continuous maintenance by trained crews, and a complete performance program, including comparison between predicted and measured performance, in areas such as pore pressure, strength, or deformations. The category Above Average would require the correction of malfunctions. However, since the category Average would not require any field measurements, the category Average to Above Average (score of 0.5) was chosen for Level of Engineering in the area Operations and Monitoring.

13) Based upon the preceding category choices in each area of the Level of Engineering, a total score of 2.4 was determined, where Above Average would have a score of 2 and Average would have a score of 3. Using the factors of safety for the East Dam in the range 1.3-1.4 (corresponding to the permitted elevation), the annual probability of failure was estimated in the range 0.2-0.8% with a best estimate of 0.4%. Using the factors of safety for the West Dam in the range 1.3-1.7 (corresponding to the permitted elevation), the annual probability of failure of the West Dam was estimated in the range 0.004-0.8% with a best estimate of 0.05%. Since the failures of either the East Dam or West Dam will result in the failure of the entire tailings management facility, the best estimate for the annual probability of failure for the entire facility is 0.45%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.1-1% (1 in 1000 to 1 in 100).
14) Based upon the historical record of tailings dam failures in British Columbia from 1969 to 2015, the annual probability of failure of a tailings dam in British Columbia is 0.17% (1 in 600). Using that information alone, and since the Copper Mountain Tailings Management Facility has two tailings dams, the annual probability of failure of the tailings facility is 0.34%, which is shockingly similar to the value that was calculated using the Silva-Lambe-Marr method. The implication is that the Level of Engineering for the tailings dams at the Copper Mountain mine is simply typical for tailings dams in British Columbia. However, it should be evident that such typical engineering is not good enough for tailings dams in the failure consequence category Extreme (corresponding to loss of more than 100 lives).
15) An annual probability of failure in the range 0.l-1% (1 in 1000 to 1 in 100) is completely unacceptable according to Canadian and US guidelines. According to the guidelines of the Canadian Dam Association, for the minimum of 100 fatalities, marginal acceptability would require annual probability of dam failure no greater than 0.001% (1 in 100,000), while broad acceptability would require annual probability of dam failure no greater than 0.00001% (1 in 10,000,000). Between marginal and broad acceptability is the As Low as Reasonably Practicable (ALARP) region in which the risk is acceptable only after risks to life have been reduced to the point where further risk reduction is impracticable or requires action that is grossly disproportionate in time, trouble, and effort to the reduction of risk achieved. The guidelines of the (US) Federal Energy Regulatory Commission and U.S. Army Corps of Engineers for existing dams provide the same values, but with slightly different vocabulary. The guidelines of the U.S. Army Corps of Engineers for new dams would require an annual probability of failure no greater than 0.0001% (1 in 1,000,000) to satisfy the Societal Tolerable Risk Limit, with the further requirement that risk is tolerable only if ALARP requirements have been satisfied.
16) Although the tailings dams are described as constructed by the "modified centerline" method, the correct terminology is "modified upstream" (which has been confirmed by the International Commission on Large Dams), since the dam raises are still constructed on top of the fine-grained, uncompacted tailings. Even so, all of the dam raises carried out between 1980 and 1996 have been explicitly described as "upstream," so that large portions of the dam are underlain by fine-grained, uncompacted tailings. The upstream construction method is the cheapest because it requires the minimal amount of construction material. The upstream construction method is also the most dangerous, since if the fine-grained tailings undergo liquefaction, the tailings dam can fail by falling into or sliding over the underlying liquefied tailings, even if the dam temporarily maintains its structural integrity. Recent

studies have documented the disproportionately large representation of upstream tailings dams among tailings dam failures and tailings dams with stability issues. For the above reasons, the upstream construction method is prohibited in Brazil, Chile, Ecuador, and Peru, and the mining industry has been steadily moving away from upstream construction, even where it is not prohibited, including in British Columbia. Apologists for the upstream construction method have argued that the method is workable if there is low precipitation, low seismicity, and high-quality personnel who cannot violate even one out of ten critical rules. Such a strict need for making no mistakes should require a Level of Engineering in the category Best, rather than the category Average to Above Average that has been observed for the tailings dams at the Copper Mountain mine.

17) There is currently a proposal to raise the permitted elevation for the Copper Mountain Tailings Management Facility to 1060 meters above sea level, corresponding to approximate heights of 259.5 meters and 251.5 meters for the East Dam and West Dam, respectively, which would make the East Dam and West Dam the second and third tallest tailings dams in the world. It is recommended that the regulatory agencies in British Columbia move forward from their current narrow focus on the factor of safety and consider the annual probability of failure, which is a standard practice in the dam industry in Canada and the USA. No such proposal, and even no further dam raising, should be entertained until the annual probability of failure of the tailings dams can be reduced to no greater than 0.001% (1 in 100,000), and even lower as required by ALARP principles.

18) If all engineering from now on were elevated to the highest standards, the Level of Engineering could be increased to 1.5 or midway between Above Average and Best. The maximum future Level of Engineering is constrained by the characteristics that cannot be fixed, such as the insufficient investigation of the foundation prior to constructing the tailings management facility. Assuming the current calculated factors of safety did not change, the minimum future annual probability of failure of the East Dam was estimated in the range 0.007-0.049% with a best estimate of 0.018%, while the minimum future annual probability of failure of the West Dam was estimated in the range 0.00005-0.007% with a best estimate of 0.002%. By summing the best estimates for the East and West Dams, the best estimate for the minimum annual probability of failure of the Copper Mountain Tailings Management Facility after improvement of engineering to the highest standards would be 0.02%. Taking into consideration the amount of judgment required in the calculation of the Level of Engineering, the annual probability of failure should be regarded as the range 0.01-0.1% even after improvement of engineering to the highest standards, which would still be too high by at least an order of magnitude, according to US and Canadian guidelines. Further recommendations for lowering the annual probability of failure of the Copper Mountain Tailings Management Facility are not obvious and are beyond the scope of this report.

RECOMMENDATIONS

This report makes the following recommendations to the Province of British Columbia:

1) The regulatory agencies in British Columbia should move forward from their current narrow focus on the factor of safety and consider the annual probability of failure, which is a standard practice in the dam industry in Canada and the USA.

2) Based on the potential loss of at least 100 lives in the event of dam failure, no further dam raising should be considered until the annual probability of failure of the Copper Mountain Tailings Management Facility can be reduced to no greater than 0.001% (1 in 100,000), and even lower as required by ALARP (As Low as Reasonably Practicable) principles, in accordance with the guidelines of the Canadian Dam Association.

ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has 70 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and non-governmental organizations. Dr. Emerman has evaluated proposed and existing tailings storage facilities in North America, South America, Europe, Africa, Asia and Oceania, and has testified on tailings storage facilities before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States, the European Parliament, the United Nations Permanent Forum on Indigenous Issues, and the United Nations Environment Assembly. Dr. Emerman is the Chair of the Body of Knowledge Subcommittee of the U.S. Society on Dams and one of the authors of Safety First: Guidelines for Responsible Mine Tailings Management.

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