The Risk of Tailings Dam Failure in British Columbia: An Analysis of the British Columbia Existing and Future Tailings Storage Database

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LIGHTNING SUMMARY

BC Mining Law Reform and SkeenaWild Conservation Trust have produced the British Columbia Existing and Future Tailings Storage Database. The 86 sites containing at least one tailings storage facility in British Columbia include 57 sites that are closed or under care and maintenance, 18 operating sites, and 11 proposed sites. This report identifies 12 sites of concern, including two proposed sites (KSM and Red Mountain Underground Gold), that are located in a seismic hazard zone Very High and/or where annual runoff exceeds 2000 mm, and with one or more of the following characteristics: (1) use of upstream or unclear dam construction method (2) site status as closed or in care and maintenance (3) dam failure consequence category High, Very High, Extreme, or unclear.

EXECUTIVE SUMMARY

BC Mining Law Reform and SkeenaWild Conservation Trust have produced the British Columbia Existing and Future Tailings Storage Database ("BC Tailings Storage Database"), which identifies every site in British Columbia that contains at least one tailings storage facility. The 86 sites containing at least one tailings storage facility in British Columbia include 57 sites that are closed or under care and maintenance, 18 operating sites, and 11 proposed sites. Because some mine sites contain multiple tailings storage facilities, the database does not detail every single tailings storage facility in the province. Among other information, for each mine site, the database provides the height of the tallest tailings dam on site, the current tailings storage volume across all tailings storage facilities at each site, the design storage capacity for the largest (greatest volume) tailings storage facility at each site, the tailings dam construction method (only in terms of whether an upstream dam is present on site or not), and the highest dam failure consequence category assigned to any tailings dam on site.

The objective of this report was to use the database to evaluate the risk of tailings dam failure in British Columbia, where risk is the combination of the probability of failure and the consequences of failure. Risk factors that increase the probability of failure are high runoff (or high precipitation), high seismicity, and the use of the upstream dam construction method. This report includes a detailed appendix that compiles and interprets information on the danger of upstream construction. Dam height can be a risk factor, although it can be compensated by an improved level of engineering that is not guaranteed and which must be verified in each case. The status of sites containing tailings storage facilities as closed or in care and maintenance is also a risk factor because it can be questioned as to whether any tailings facility on site that has credible failure modes is still receiving adequate monitoring, inspection and maintenance, without which failure should be regarded as inevitable. Even if monitoring, inspection and

maintenance are ongoing, it can still be questioned as to whether the facility was ever constructed to be able to withstand the appropriate design flood and design earthquake. Risk factors that increase the consequences of failure are dam height and storage volume of the facility. The preceding risk factors should be implicitly incorporated into the dam failure consequence category, which depends upon the potential loss of life, as well as the impacts to environmental and cultural values, and to infrastructure and economics. The five failure consequence categories of the Canadian Dam Association are Low, Significant, High (potential loss of 10 or fewer lives), Very High (potential loss of 100 or fewer lives), and Extreme (potential loss of more than 100 lives).

The progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites shows a steady increase in both size and the severity of consequences in the event of tailings dam failure. The mean heights of the tallest dams at closed sites and sites under care and maintenance, operating sites, and proposed sites are 36.8 meters, 65.5 meters, and 123.9 meters, respectively. The mean current site-wide tailings storage volumes at sites that are closed or under care and maintenance, and operating sites are 22.7 and 121.5 million cubic meters, respectively. Based on the largest tailing facility on each site, the mean design tailings storage capacities at sites that are closed or under care and maintenance, operating sites, and proposed sites are 11.6 million cubic meters, 205.2 million cubic meters, and 362.3 million cubic meters, respectively. Considering only sites with a known failure consequence category, for closed sites or sites under care and maintenance, 45.8% have dams in the combined High, Very High and Extreme consequence categories (implying potential loss of life), while 83.3% of operating sites have dams in the combined High, Very High, and Extreme consequence categories. Of the 11 proposed sites containing tailings storage facilities, four have dams in the consequence category Very High, one has at least one dam in the consequence category Extreme, one has failure consequence category N/A, and the rest are not yet known. The lack of any proposed sites where tailings dams are all in the failure consequence categories Low, Significant or High suggests that it is no longer economically possible to construct a tailings storage facility for which failure would result in the potential loss of fewer than 10 lives.

The 57 sites that are closed or under care and maintenance include 14 with tailings dams constructed using the upstream method and an additional seven sites for which tailings dam construction method is unclear. The 14 sites with upstream dams that are either closed or under care and maintenance include three where the highest dam failure consequence is High and four where it is Very High. For sites for which dam construction method is unclear, the dam failure consequence category is likewise unclear, except for one in the Low consequence category. The 18 operating sites include five with tailings dams constructed using the upstream method, including one, two and two where the highest dam failure consequence categories are High, Very High and Extreme, respectively. Excluding proposed sites and sites for which dam failure consequence categories are unclear, 12 out of 19 sites (63.2%) with upstream dams are also in the combined High, Very High and Extreme consequence categories, while 25 out of 46 (54.3%) sites without upstream dams are in the combined High, Very High and Extreme consequence categories. Excluding proposed sites, the mean height of the tallest dams at sites with upstream dams and without upstream dams are 58.4 meters and 40.3 meters, respectively. The seven sites with tailings dams in the consequence category Extreme include one closed site, five operating sites, and one proposed site. There are no proposed upstream tailings dams, except for one site for which the dam construction method is still unclear, which is consistent with the global trend on the part of the mining industry to move away from upstream construction, even where it is not prohibited.

Sites with tailings storage facilities of concern were identified by comparing site locations with maps of seismic hazard zones and annual runoff. The criteria for a site of concern were location in a seismic hazard zone Very High and/or where annual runoff exceeds 2000 mm, and with one or more of the following characteristics: (1) use of upstream or unclear dam construction method (2) site status as closed or in care and maintenance (3) dam failure consequence category High, Very High, Extreme, or unclear. The 12 sites containing tailings storage facilities of concern included nine sites that are closed or in care and maintenance (Benson Lake, Bolivar/Yew Project/Texada Island Project, Eskay Creek, Johnny Mountain, New Privateer/Privateer/Zeballos, Northair, Premier Gold/Red Mountain, Quinsam North Pit, Snip), one operating site (Myra Falls), and two proposed sites (KSM, Red Mountain Underground Gold). The two proposed sites KSM and Red Mountain Underground Gold have dams with failure consequence categories Extreme and Very High, respectively. The existence of proposed sites among sites with tailings storage facilities of concern cannot be overemphasized.

A comparison between locations of sites containing tailings storage facilities in British Columbia with salmon habitat and municipal boundaries reveals considerable threat to both communities and wildlife. Out of the 86 sites containing tailings storage facilities (including proposed sites), 54 are located within salmon habitat. The many municipalities along the lower Fraser River should be regarded as particularly vulnerable to tailings dam failure at any of the 27 existing and proposed sites containing tailings storage facilities within the watershed of the Fraser River. As a single example, if the failure of the largest tailings storage facility at the HVC – Highland site released all stored tailings at the maximum capacity, nearly 1500 million cubic meters of toxic tailings would flow through the cities along the lower Fraser River. A partial list of potentially impacted cities along the lower Fraser River includes Abbotsford (population 151,683), Burnaby (population 202,799), Coquitlam (population 114,656), Delta (population 101,668), Richmond (population 182,000), Surrey (population 394,976), and Vancouver (population 600,000).

The risk of tailings dam failure in British Columbia has probably been underestimated since the BC Tailings Storage Database counts dams as non-upstream that are listed in mining company or government documents as constructed using the "modified centerline" method. For example, the mining company Centerra Gold lists the closed Kemess South/Kemess Underground (KUG) tailings storage facility (with a height of 180 meters) as constructed by the "modified centerline" method. The phrase "modified centerline" is non-standard terminology because the dam is still constructed on top of the uncompacted tailings (in the manner of an upstream dam). The correct terminology is "modified upstream" (which has been confirmed by the International Commission on Large Dams), so that the number of sites with upstream dams in the BC Tailings Storage Database has been undercounted. It is particularly important to determine whether any dams at proposed sites with tailings storage facilities have been labeled as "modified centerline."

This report makes the following recommendation to the creators of the BC Tailings Storage Database:

1) The database should indicate whether tailings dams have been labeled as "modified centerline" and should count these as upstream dams.
2) The database should indicate whether any portion of a tailings storage facility has been constructed on top of previously-existing tailings.

3) Sites should not be removed from the database until it has been convincingly demonstrated that the tailings storage facilities on the site have no remaining credible failure modes.

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

1) Serious consideration should be given as to the wisdom of permitting two proposed sites (KSM and Red Mountain Underground Gold) that have been identified as sites with tailings storage facilities of concern.
2) Serious consideration should be given to the designation N/A for the failure consequence category for a tailings storage facility, in terms of whether there truly are no credible failure modes. This consideration especially applies to the proposed site Roman Coal Mine/Trend-Roman.
3) Serious consideration should be given to the fact that, out of all options for stabilizing tailings dams at risk of failure or for safeguarding downstream communities, denying a permit for a facility that does not yet exist is by far the least expensive.

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OVERVIEW

Mine tailings are the wet and crushed rock or solid particles that remain after the commodity of value has been extracted from the ore. It is most typical that the tailings are permanently stored aboveground within a tailings storage facility. BC Mining Law Reform and SkeenaWild Conservation Trust have produced the British Columbia Existing and Future Tailings Storage Database ("BC Tailings Storage Database"), which identifies every site in British Columbia that contains at least one tailings storage facility. The 86 sites containing at least one tailings storage facility in British Columbia include 57 sites that are closed or under care and maintenance, 18 operating sites, and 11 proposed sites (see selections from database in Tables 1a-c, 2 and 3). Because some mine sites contain multiple tailings storage facilities, the database does not detail every single tailings storage facility in the province.

Table 1a. Sites with upstream tailings dams: Closed and Care & Maintenance[1,2,3]

Mine	Maximum Dam Height (m)	Current Site Storage (Mm^3)	Largest Facility Capacity (Mm^3)	Highest Failure Consequence Category
Blackdome	36	—	—	Significant
Craigmont	16	—	0.279	Significant
Dankoe	30	—	—	Low
Endako	147	216	115	High
Giant Nickel/Pride of Emory	25	2.18	1.34	Very High
Golden Bear	5	—	—	Low
Granisle	75	34	30	Low
HVC - Bethlehem	91	68.1	—	Very High
Mount Polley	52	—	83.30222	Significant
Nickel Plate	60	7.6	8.2	Very High
Premier Gold/Red Mountain	51	1.35	2.62	Very High
Shasta/Multinational B & Baker Mill	23	0.169403	—	Significant
Silvana/Klondike Silver/Hinckley	22	0.2	0.2	High
Sullivan	29	47	—	High

[1]Data from BC Tailings Storage Database
[2]Dashes indicate unknown information.
[3]Mm^3 = million cubic meters

The BC Tailings Storage Database is a considerable advance over anything that has existed before. The new database contains considerably more information and documentation than its predecessor, the British Columbia Tailings Storage Facility Inventory (Independent Expert Engineering Investigation and Review Panel, 2015a). Although the British Columbia Tailings Storage Facility Inventory includes 181 entries, those entries refer to individual tailings dams (or embankments) that encompass fewer mine sites than the new BC Tailings Storage Database. The Inventory of Large Dams in Canada 2019 does not even include any tailings dams (Canadian Dam Association, 2019a). Other global and national tailings dam databases include the Global Tailings Portal (Franks et al., 2021; GRID-Arendal, 2022), the (Brazil) *Sistema Integrado de Gestão de Barragens de Mineração* [Integrated Management System for Mining Dams] (ANM, 2022), the *Depósito de Relaves—Catastro de Depósitos de Relaves en Chile*

[Tailings Deposit—Registry of Tailings Deposits in Chile] (SNGM, 2020), the (Mexico) *Inventario Homologado Preliminar de Presas de Jales* [Preliminary Approved Inventory of Tailings Dams] (Secretaría de Medio Ambiente y Recursos Naturales (México) [Secretariat of Environment and Natural Resources (Mexico)], 2022), the (Peru) *Geografias en Conflicto* [Geographies in Conflict] (CooperAcción, 2022), the (Spain) *Inventario Nacional de Depósitos de Lodos 2002* [National Inventory of Sludge Deposits 2002] (Rodríguez Pacheco and Gómez De Las Heras, 2006; IGME, 2022), and the (USA) National Inventory of Dams (USACE, 2022). More information about other tailings dam databases can be found in the Appendix in the subsection Emerging Tailings Dam Databases.

Table 1b. Sites with unclear dam construction method: Closed and Care & Maintenance[1,2,3]

Mine	Max Dam Height (m)	Current Site Storage (Mm^3)	Largest Facility Capacity (Mm^3)	Highest Failure Consequence Category
Benson Lake	—	—	—	Unclear
Bolivar/Yew Project/Texada Island Project	—	—	—	Unclear
Lawyers/Cheni	20	0.477	—	Unclear
Mount Copeland	7	0.08	—	Unclear
New Privateer/Privateer/Zeballos	10	—	—	Unclear
Northair	—	—	0.1	Unclear
Taurus Gold	—	—	0.056	Low

[1]Data from BC Tailings Storage Database
[2]Dashes indicate unknown information.
[3]Mm^3 = million cubic meters

Table 1c. Sites with upstream tailings dams: Operating[1,2,3]

Mine	Maximum Dam Height (m)	Current Site Storage (Mm^3)	Largest Facility Capacity (Mm^3)	Highest Failure Consequence Category
Copper Mountain	160	200	250	Extreme
Elkview - West Fork	59	37.4186	22.760	Very High
Gibraltar - TSF	117	—	70.8	Extreme
HVC - Trojan	70	26	—	Very High
Myra Falls	41	—	5.8	High

[1]Data from BC Tailings Storage Database
[2]Dashes indicate unknown information.
[3]Mm^3 = million cubic meters

The BC Tailings Storage Database has a data structure that is unique among existing tailings dam databases. Each of the 86 entries refers to a mine site. Among other information, each entry includes the maximum tailings dam height (the height of the tallest tailings dam on site), the current tailings storage volume across all tailings storage facilities at each site, the design storage capacity for the largest (greatest volume) tailings facility at each site, the tailings dam construction method (only in terms of whether an upstream dam is present on site or not), and the highest dam failure consequence category assigned to any tailings dam on site. There are cases in the database where this information all refers to a single tailings storage facility (i.e., the only facility) on a mine site, and other cases where this information may refer to different tailings storage facilities on a single mine site. Not all information is available for all sites. For three sites (Silvana/Klondike Silver/Hinckley, Blackwater Gold, Kutcho; see Tables 1a and 2), the design storage capacity refers not to the largest tailings storage facility, but to the sum over all tailings storage facilities.

Table 2. Proposed sites with tailings storage facilities[1,2,3]

Mine	Upstream Dam Present	Maximum Dam Height (m)	Largest Facility Capacity (Mm^3)	Highest Failure Consequence Category
Ajax	No	131	220	Very High
Aley	No	—	—	Unclear
Blackwater Gold	No	100	462[4]	Very High
Dome Mountain	Unclear	—	—	Unclear
Galore Creek	No	165	339	Unclear
KSM	No	239	1150	Extreme
Kutcho	No	57	3.25[4]	Unclear
New Prosperity	No	120	460	Very High
Red Mountain Underground Gold	No	55	1.54	Very High
Roman Coal Mine/Trend-Roman	No	N/A	3.1	N/A
Ruddock Creek	No	—	—	Unclear

[1]Data from BC Tailings Storage Database
[2]Dashes indicate unknown information.
[3]Mm^3 = million cubic meters
[4]Refers to design capacity for the entire proposed site, as opposed to just the largest tailings facility on site

Table 3. Sites with tailings dams in the Extreme failure consequence category[1,2,3]

Mine	Status	Upstream Dam Present	Maximum Dam Height (m)	Current Site Storage (Mm^3)	Largest Facility Capacity (Mm^3)
Brenda	Closed	No	137	133	—
Copper Mountain	Operating	Yes	160	200	250
Gibraltar - TSF	Operating	Yes	117	—	70.8
HVC - Highland	Operating	No	162	1190.3	1477.971
KSM	Proposed	No	239	N/A	1150
New Afton - HATSF	Operating	No	60	22.5	—
New Afton - NATSF	Operating	No	57	29.113659	—

[1]Data from BC Tailings Storage Database
[2]Dashes indicate unknown information.
[3]Mm^3 = million cubic meters

The objective of this report is to answer the following question: Based on an analysis of the BC Tailings Storage Database, what is the risk of tailings dam failure in British Columbia? The question requires some clarification of vocabulary. In the mining literature, the term “tailings dam” can refer either just to the containing structure (the dam or embankment) or to the combination of the containing structure plus the contained materials (tailings and water). The term “tailings storage facility” always refers to the containing structure plus the contained materials plus any associated infrastructure, such as channels for diverting surface runoff around the facility. For example, according to ANCOLD (2012), a tailings dam is “a structure or embankment that is built to retain tailings and/or to manage water associated with the storage of tailings, and includes the contents of the structure,” while a tailings storage facility “includes the tailings storage, containment embankments and associated infrastructure.” However, in the BC Tailings Storage Database, “tailings dam” refers to just the containing structure and that language will be used in this report. In this way, a single tailings storage facility could have multiple tailings dams. For example, the tailings storage facility at the Copper Mountain mine site is within a valley and is confined by the natural topography and two tailings dams at either end of the valley (called Copper Mountain Tailings Storage Facility East Dam and Copper Mountain Tailings Storage Facility West Dam (Independent Expert Engineering Investigation and Review Panel (2015a)). Because each entry in the BC Tailings Storage Database represents a mine site, some entries may represent multiple tailings storage facilities, in addition to representing multiple tailings dams.

Some consideration is necessary for the meaning of the term “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.).” 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. Although “tailings dam” and “tailings storage facility” are somewhat different concepts, it should be clear that any failure of the tailings dam also constitutes a failure of the tailings storage facility.

Prior to a discussion of the methodology for addressing the objective, this report includes a summary of the risk factors for tailings dam failure. In addition, there is a detailed Appendix for readers who are not specialists in tailings dams. The first two subsections of the Appendix (Tailings Dams and Water-Retention Dams, Methods of Construction of Tailings Dams) should be read at this point by readers who are encountering tailings dams for the first time. The next six subsections of the Appendix (Causes of Failure of Tailings Dams, Construction Methods and Causes of Failure, Cause of Failure of the Tailings Dam at Brumadinho, Emerging Tailings Dam Databases, Post-Brumadinho Guidance and Data on Upstream Dams, Post-Brumadinho Guidance on Brittle Tailings: Implications for Upstream Dams) are primarily intended to persuade the reader of the unacceptable risk posed by the method of upstream construction for tailings dams. I am not aware of any other resource that compiles and interprets all of the pertinent information on the danger of the upstream construction method. The next subsection (Modified Centerline and Hybrid Tailings Dams) is background for understanding my recommendations for improvement of the BC Tailings Storage Database. The final subsection

(Effect of Height on Risk of Failure of Tailings Dams) reviews the ambiguous effect of dam height on risk and is background for a full comprehension of the discussion of risk factors for tailings dam failure. The inevitability of failure of closed tailings dams is so critical to this report that the subject is discussed both in the first subsection (Tailings Dams and Water-Retention Dams) of the Appendix and in the following section.

SUMMARY OF RISK FACTORS FOR TAILINGS DAM FAILURE

The purpose of this section is to summarize the risk factors for tailings dam failure. The Appendix should be consulted for further information on this subject, especially on the impacts of height and the upstream construction method on the risk of failure. The risk of tailings dam failure is understood as the combination of (or the product of) the probability of failure and the consequences of failure. Risk factors that increase the probability of failure are high runoff (or high precipitation), high seismicity, and the use of the upstream construction method. From a purely physical standpoint, height is a risk factor because it increases the gravitational stress on a tailings dam. The data on the impact of height on the probability of failure is ambiguous, largely because an improved level of engineering can overcompensate for the increased gravitational stress. It is important to note that the required improved level of engineering cannot be guaranteed and must be verified in each case.

The status of sites containing tailings storage facilities as closed or in care and maintenance is also a risk factor because it can be questioned as to whether a tailings facility that is no longer operating is still receiving adequate monitoring, inspection and maintenance. This ongoing monitoring, inspection and maintenance is necessary as long as a tailings storage facility still has credible failure modes. A failure mode is any sequence of events that could potentially lead to tailings dam failure. In this context, "credible" simply means that a failure mode is physically possible and is unrelated to the likelihood of the failure mode. The Global Industry Standard on Tailings Management has emphasized that "the term 'credible failure mode' is not associated with a probability of this event occurring" (ICMM-UNEP-PRI, 2020). There are not many situations in which a closed tailings storage facility could be described as having no credible failure modes. One example could be the placement of tailings into an exhausted open pit surrounded by a dike, with the top of the tailings or tailings pond at such a depth that even the Probable Maximum Flood (PMF), that is, the greatest flood that is theoretically possible at a given location, could not raise the tailings or any associated supernatant water to the top of the dike. Even in that case, it could be questioned as to whether the PMF, as it is understood at the present time, is the same PMF that could occur after decades or centuries of climate change.

The important point is that, if any closed tailings storage facility that still has credible failure modes is not receiving adequate monitoring, inspection and maintenance, its failure should be regarded as inevitable. By analogy, 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, a tailings dam is expected to confine the toxic tailings in perpetuity. Thus, a tailings dam can never be dismantled unless the tailings can be moved to another location, such as an abandoned open pit.

The inevitability of tailings dam failure is generally understood in the tailings dam literature. 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, 2015b), has argued that, since tailings dam failure 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.”

Although tailings dam failure could in principle be avoided by ongoing and adequate monitoring, inspection and maintenance, the realism of perpetual monitoring, inspection and maintenance requires careful consideration. In Tailings Dam Management for the Twenty-First Century, Oboni and Oboni (2020) mocked the concept of perpetual maintenance by writing, “There are plenty of cases where the ‘P’ word, ‘perpetuity’ is used. Just remember, perpetuity is way longer than a long time! … If we had closed our mining tailings facility 1000, 500, or 200 years ago, would we have expected that the tailings (mining waste) should still be right there where we dumped them, unattended, not maintained, not monitored? Oh, we are forgetting one thing: had we left a Standard Operating Procedure and Maintenance Manual for ‘future generations,’ now the manual would be in a language difficult (if not impossible) to understand. The documents might have turned to dust or have been heavily damaged. In addition, if we think digital transcriptions of our documents may have saved us, the solar flare of 1859 (the Carrington event) would probably have erased them if all fires, floods, and wars had not destroyed them earlier.” Oboni and Oboni (2020) are reinforcing the point of Vick (2014a-b) in arguing that over the long term (several centuries), there are too many things that can go wrong to imagine that closed tailings dams could survive either with or without the intention of perpetual maintenance.

It is the case that, at least at the present time, most closed tailings storage facilities in British Columbia are receiving annual dam safety inspections. Even in the relatively short term (decades after tailings dam closure), it cannot be assumed that annual dam safety inspections are a guarantee of safety. Annual dam safety inspections are typically visual inspections and consider only the changes that may have occurred since the previous inspection. It is very rare for annual dam safety inspections to take a holistic view of the entire history of a tailings dam. Thus, annual dam safety inspections are very poor at anticipating brittle failure modes, such as static liquefaction or foundation failure, which could occur without precursors. 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.” Moreover, annual dam safety inspections do not necessarily lead to appropriate maintenance and mitigation. In fact, the author is aware of annual dam safety inspections, even of operating tailings facilities, that are simply documenting the progress toward failure.

Even if monitoring, inspection and maintenance are ongoing, it can still be questioned as to whether the facility was ever constructed to be able to withstand the appropriate design flood and design earthquake. Even if the facility were originally constructed to be able to withstand a particular design flood, such as a 1000-year storm, future climate change could transform what was once a 1000-year storm into a storm with a shorter return period. The appropriate design flood and design earthquake depend upon the consequences of dam failure and the consequences could change as there is a future change in the social or environmental context of a tailings facility. It has already been noted that such considerations would not be typical considerations in annual dam safety inspections.

There are, in fact, many other risk factors that could increase the probability of failure. Some of these are design features, such as a permanent water cover on the tailings or the lack of thickening the tailings before they are shipped to the tailings storage facility. Other risk factors are accidental features, such as the lack of adequate characterization of the foundation before construction of the tailings storage facility. These intentional and accidental risk factors are not considered in this report, simply because information about these other risk factors is not included in the BC Tailings Storage Database. Although the runoff (or precipitation) and seismicity at each site with tailings storage facilities are also not included in the BC Tailings Storage Database, this information is readily available from government sources (see Methodology section). Thus, in terms of probability of failure, this report focuses only on runoff, seismicity, dam construction method (whether an upstream dam is present on site), dam height (height of the tallest dam on site) and site status (closed, care and maintenance, operating, or proposed).

Risk factors that could increase the consequences of failure and which are included in the BC Tailings Storage Database include dam height (height of the tallest dam on site) and site-wide current storage volume (volume of tailings currently stored across all tailings facilities on site). Taller dams result in greater release of gravitational potential energy as the tailings fall out of the tailings storage facility and, thus, a longer runout (initial travel distance) of the tailings. Of course, a greater storage volume results in a greater potential release of tailings and there are cases in which tailings dam failure has resulted in the loss of 100% of the stored tailings. Some examples of total losses of tailings include the failure of the El Cobre New Dam in Chile in March 1965 (350,000 cubic meters), and the failures at the Pittston Coal mine in Buffalo Creek, West Virginia (USA) in February 1972 (500,000 cubic meters), the United Nuclear uranium mine in Churchrock, New Mexico in July 1979 (370,000 cubic meters), and the Louyang Xiangjiang Wanji aluminum mine in China in August 2016 (2 million cubic meters) (Center for Science in Public Participation, 2022). The storage capacity (design storage capacity for the largest tailings facility on site) listed in the BC Tailings Storage Database indicates the potential loss of tailings at maximum buildout of the tailings storage facility. Proposed sites have no current storage volume, so that only the storage capacity is meaningful.

The consequences of failure relate not only to the extent, depth and velocity of the tailings flood, but the social and environmental context into which the tailings flood occurs. The Canadian Dam Association (2013) considers five dam failure consequence categories (Low, Significant, High, Very High, Extreme) that should implicitly incorporate the tailings dam height and current storage volume, as well as the social and environmental context (see Fig. 1). The five dam failure consequence categories are based upon potential loss of life, as well as impacts on environmental and cultural values, and on infrastructure and economics. For this report, the most important categories are High, Very High, and Extreme, corresponding to potential losses of 10 or fewer lives, 100 or fewer lives, and more than 100 lives, respectively (see Fig. 1). It should be noted that, although the tailings dam failure at the Mount Polley mine was one of the greatest environmental disasters in Canadian history, its failure consequence category was only in the Significant category because there was negligible potential for loss of human life. In the same way, the tailings dam at the Mount Polley mine, presently in care and maintenance, continues to be in the failure consequence category Significant.

METHODOLOGY

Based upon the preceding sections, the objective of this study can be subdivided into the following questions:

1) With regard to other risk factors, how do sites containing tailings storage facilities compare with respect to status (closed, care and maintenance, operating, proposed) in British Columbia?
2) With regard to other risk factors, how do sites with upstream tailings dams compare with sites without upstream tailings dams in British Columbia?
3) With regard to other risk factors, how do sites containing tailings storage facilities compare with respect to dam failure consequence categories in British Columbia?
4) Based upon the information in the BC Tailings Storage Database, which are the particular sites with tailings storage facilities of concern in British Columbia?
5) What are the potential impacts of tailings dam failure on salmon and communities in British Columbia?

For the analysis of this report, sites listed as “Closed” and sites listed as under “Care and Maintenance” were treated as a single category. The BC Tailings Storage Database lists 34 sites with the status “Closed” and 23 sites with the status “Care and Maintenance.” Although mining company and governmental documents sometimes use one term and sometimes another, the distinction between the two is not obvious. The expression “care and maintenance” does not appear in any of the mining regulations or guidance documents in British Columbia (Ministry of Energy and Mines (British Columbia), 2016, 2017; BC Laws, 2022a-b), except in the context of “the care and maintenance of all rescue apparatus” (Ministry of Energy and Mines (British Columbia), 2017).

Table 2-1: Dam Classification

Dam class	Population at risk [note 1]	Incremental losses		
		Loss of life [note 2]	Environmental and cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss No long-term loss	Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat Loss of marginal habitat only Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of *important* fish or wildlife habitat Restoration or compensation in kind highly possible	High economic losses affecting infrastructure, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of *critical* fish or wildlife habitat Restoration or compensation in kind possible but impractical	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of *critical* fish or wildlife habitat Restoration or compensation in kind impossible	Extreme losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances)

Note 1. Definitions for population at risk:

None—There is no identifiable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure.

Temporary—People are only temporarily in the dam-breach inundation zone (e.g., seasonal cottage use, passing through on transportation routes, participating in recreational activities).

Permanent—The population at risk is ordinarily located in the dam-breach inundation zone (e.g., as permanent residents); three consequence classes (high, very high, extreme) are proposed to allow for more detailed estimates of potential loss of life (to assist in decision-making if the appropriate analysis is carried out).

Note 2. Implications for loss of life:

Unspecified—The appropriate level of safety required at a dam where people are temporarily at risk depends on the number of people, the exposure time, the nature of their activity, and other conditions. A higher class could be appropriate, depending on the requirements. However, the design flood requirement, for example, might not be higher if the temporary population is not likely to be present during the flood season.

Figure 1. The Canadian Dam Association (2013) has five dam failure consequence categories, of which High, Very and Extreme, involve the potential loss of 10 or fewer lives, 100 or fewer lives, or more than 100 lives, respectively. Table from Canadian Dam Association (2013).

Sometimes the expression “Care and Maintenance” is used to imply a plan to restart mining operations (for example, after a rise in commodity prices), while “Closed” implies the absence of such a plan. However, this usage is not codified in British Columbia regulations or guidance documents and is not consistent throughout the mining industry. For example, according to ICMM (2019), “During temporary closure, the site is maintained. This is also called a ‘care and maintenance phase’”. On the other hand, ICMM (2019) also states, “The benefits of this integration [into life of mine planning] can include the following: … reduce risk of an extended period of care and maintenance at the end of the mine life due to inadequate closure planning … The following are standard closure principles widely used and considered good practice: … Long-term care: to design the closure plan to minimise or eliminate the need for long-term post-closure care and maintenance.” In other words, ICMM (2019) envisions “care and maintenance” either as a temporary phase prior to re-starting the mine or as an extended period that occurs after mine closure. From another perspective, ANCOLD (2012) defines “mine closure” as “A process being undertaken between the time when the operating stage of a mine is ending or has ended and the final decommissioning or rehabilitation is completed. Closure may only be temporary or may lead to a period of care and maintenance.” In that sense, “care and maintenance” is regarded as the opposite of temporary closure, but still with the implication that it is only “a period,” rather than a permanent condition. Finally, according to Canadian Dam Association (2019b), “For the case where the mining dam has been designed to accommodate a water treatment system, this phase [Closure – Active Care] would involve ongoing operation, maintenance and surveillance, and possibly management of the water levels. This phase is often referred to as ‘care and maintenance.’ In many cases, these activities could last for decades or centuries.” The admission that “Care and Maintenance” could last for centuries is certainly not consistent with a plan to restart mining operations. As discussed in the section Summary of Risk Factors for Tailings Dam Failure, tailings storage facilities that are not receiving adequate monitoring, inspection, and maintenance (which could be referred to as “care and maintenance”) should be regarded as abandoned and their failure should be regarded as inevitable.

Sites containing tailings storage facilities of concern in British Columbia were identified by comparing site locations with maps of seismic hazard zones and annual runoff. The criteria for a site of concern were location in a seismic hazard zone Very High and/or where annual runoff exceeds 2000 mm, and with one or more of the following characteristics: (1) use of upstream or unclear dam construction method (2) site status as closed or in care and maintenance (3) dam failure consequence category High, Very High, Extreme, or unclear. The shapefile for average annual runoff in Canada (1971 to 2013) was obtained from Government of Canada (2022a). A shapefile for seismic hazard zones in British Columbia was constructed by tracing from the “Simplified Seismic Hazard Map for Canada, the Provinces and Territories” available from Government of Canada (2022b). Although this report labels seismic hazard zones as Very Low, Low, Medium, High, and Very High, Government of Canada (2022b) uses five colors without any labels. Shapefiles for rivers, fish ranges, municipal boundaries, and major watersheds were obtained from Government of British Columbia (2022a-d). All two-way statistical comparisons were carried out using the t-test (unpaired, unequal variance), while all comparisons over multiple datasets were carried out using the single factor ANOVA (Analysis of Variance) test. Both tests produce a P-value, which is the probability that the difference between the means of two datasets is statistically insignificant (in the case of the t-test) or the probability that the difference between at least two of the means of multiple datasets is statistically insignificant (in the case of the ANOVA test). Further aspects of the methodology will be introduced in the Results section.

RESULTS

Comparison of Sites with Tailings Storage Facilities by Status

The progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites shows a steady increase in the height of the tallest tailings dam. According to the t-test, the increase in the mean height of the tallest dam from 36.8 meters for the sites that are closed or under care and maintenance to 65.5 meters for the operating sites is statistically significant at better than the 95% confidence level ($P = 0.03$) (see Fig. 2a). On the other hand, according to the t-test, the increase in the mean height of the tallest dam from 65.5 meters for the operating sites to 123.9 meters for the proposed sites is not statistically significant at the 95% confidence level ($P = 0.06$) (see Fig. 2a). The ANOVA test clarifies that the difference between at least two mean heights is statistically significant at better than the 99.999% confidence level ($P = 7.0 \times 10^{-6}$) (see Fig. 2a). According to the t-test, the difference between the mean site storage at the sites that are closed or under care and maintenance (22.7 million cubic meters) and the operating sites (121.5 million cubic meters) is not statistically significant ($P = 0.26$) (see Fig. 2b).

The progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites also shows a steady increase in the design capacity of the largest tailings storage facility. According to the t-test, the increase in the mean of the largest storage facility capacity from 11.6 million cubic meters for the sites that are closed or under care and maintenance to 205.2 million cubic meters for the operating sites is not statistically significant at the 95% confidence level ($P = 0.14$) (see Fig. 2c). According to the t-test, the increase in the mean of the largest storage facility capacity from 205.2 million cubic meters for the operating sites to 362.3 million cubic meters for the proposed sites is also not statistically significant at the 95% confidence level ($P = 0.48$) (see Fig. 2c). The difference that is statistically significant at the 95% confidence level is the increase in the mean of the largest storage facility capacity for the sites that are closed or under care and maintenance to the proposed sites ($P = 0.05$) (see Fig. 2c). The ANOVA test clarifies that the difference between at least two mean largest storage facility capacities is statistically significant at better than the 99% confidence level ($P = 0.002$) (see Fig. 2c). The preceding values do not include three sites for which only the design capacity for the entire site is known. These include one site under care and maintenance (Silvana/Klondike Silver/Hinckley with storage capacity of 0.2 million cubic meters) and two proposed sites (Blackwater Gold with 462 million cubic meters and Kutcho with 3.25 million cubic meters).

Finally, the progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites shows a steady increase in the severity of consequences in the event of tailings dam failure. Considering only sites with a known dam failure consequence category, for closed sites or sites under care and maintenance, 45.8% have dams in the combined High, Very High and Extreme consequence categories (implying potential loss of life), while 83.3% of operating sites have dams in the High, Very High, and Extreme consequence categories (see Table 4a). Of the 11 proposed sites with tailings storage facilities, four have dams in the consequence category Very High, one has one or more dams in the consequence category Extreme, one has consequence category N/A, and the rest are not yet known (see Tables 2 and 4a). The significance of the failure consequence category N/A will be addressed in the Discussion section.

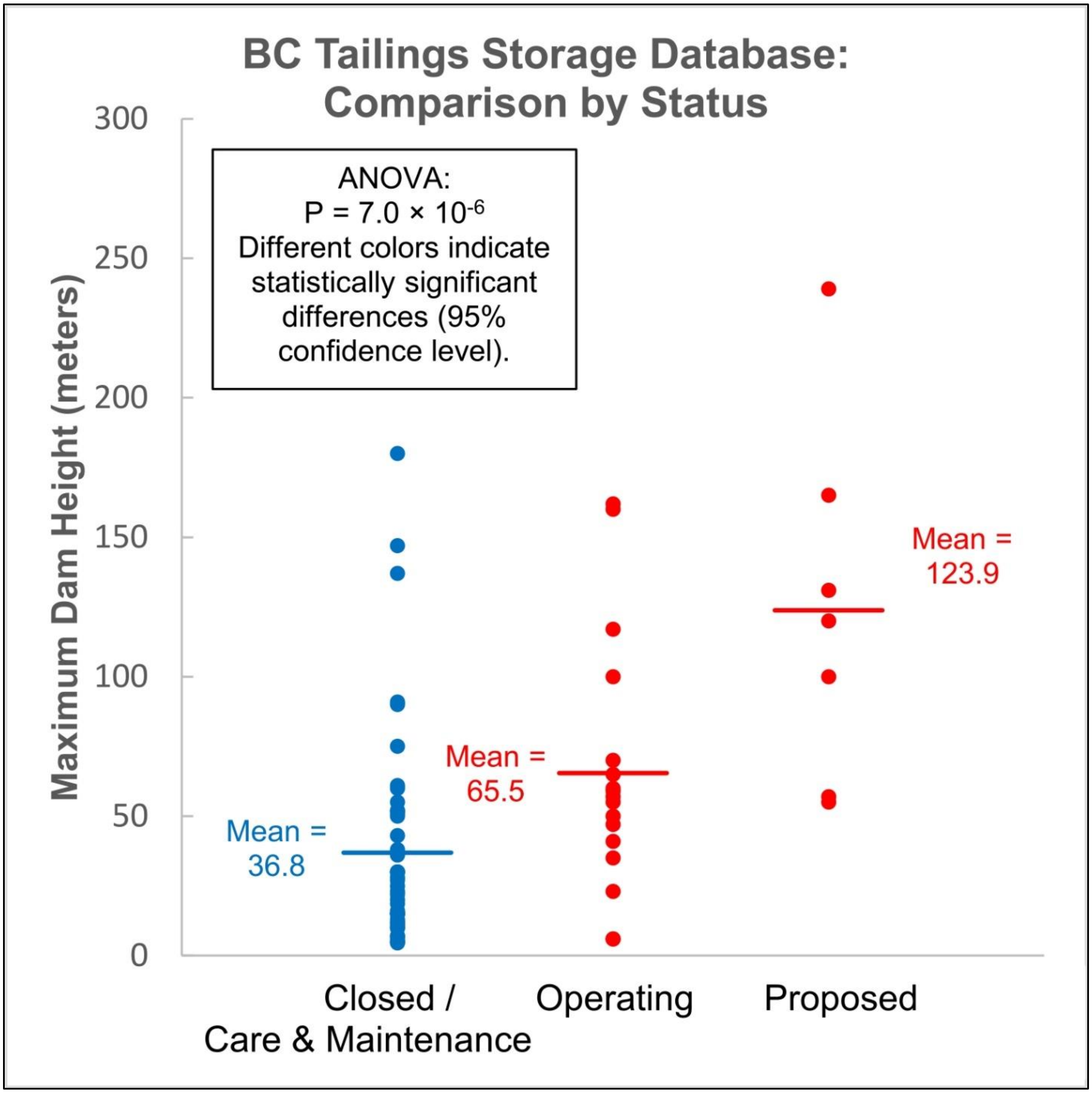

Figure 2a. For the BC Tailings Storage Database, the heights of the tallest tailings dams per site were compared among the 57 sites that are closed or under care and maintenance, the 18 operating sites, and the 11 proposed sites. According to the t-test, the increase in the mean height of the tallest dam from 36.8 meters for the sites that are closed or under care and maintenance to 65.5 meters for the operating sites is statistically significant at better than the 95% confidence level ($P = 0.03$). According to the t-test, the increase in the mean height of the tallest dam from 65.5 meters for the operating sites to 123.9 meters for the proposed sites is not statistically significant at the 95% confidence level ($P = 0.06$). The ANOVA test clarifies that the difference between at least two mean heights is statistically significant at better than the 99.999% confidence level ($P = 7.0 \times 10^{-6}$).

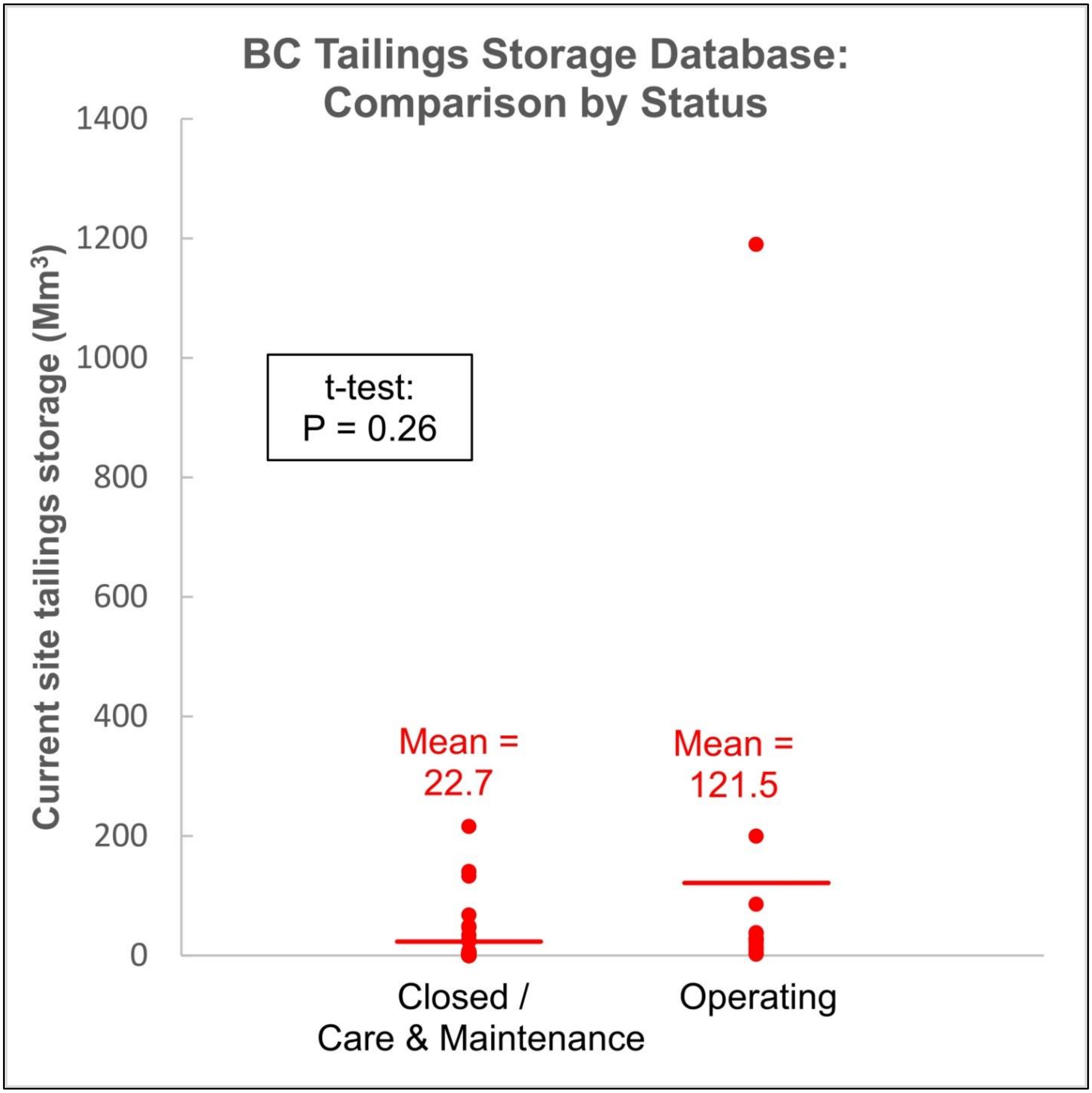

Figure 2b. For the BC Tailings Storage Database, the site-wide tailings storage volumes were compared between the 57 sites that are closed or under care and maintenance and the 18 operating sites. According to the t-test, the difference between the mean site storage at the sites that are closed or under care and maintenance (22.7 million cubic meters) and the operating sites (121.5 million cubic meters) is not statistically significant (*P* = 0.26).

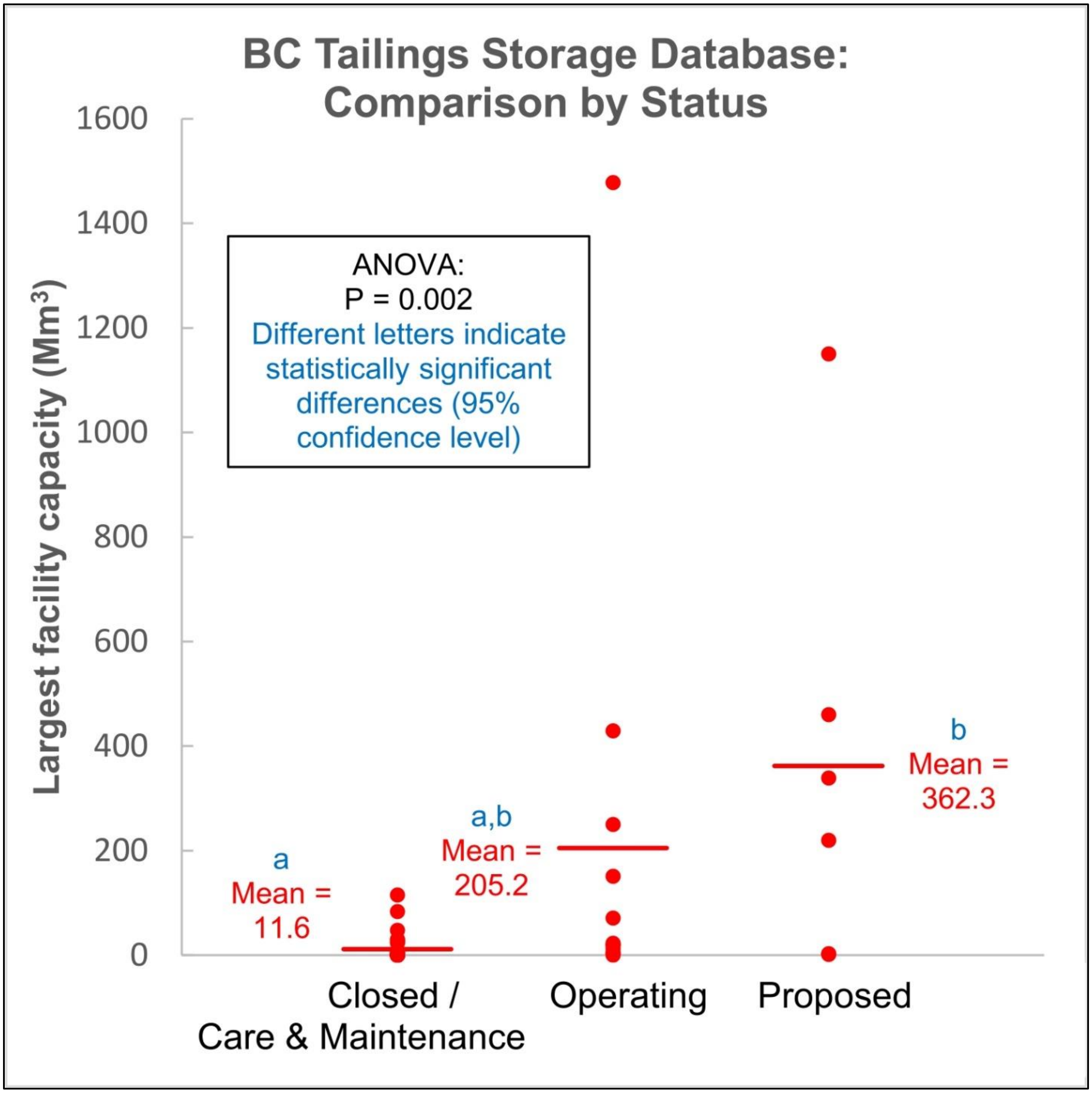

Figure 2c. For the BC Tailings Storage Database, the largest facility storage capacities were compared among the 57 sites that are closed or under care and maintenance, the 18 operating sites, and the 11 proposed sites. According to the t-test, the increase in the mean of the largest storage facility capacity from 11.6 million cubic meters for the sites that are closed or under care and maintenance to 205.2 million cubic meters for the operating sites is not statistically significant at the 95% confidence level ($P = 0.14$). According to the t-test, the increase in the mean of the largest storage facility capacity from 205.2 million cubic meters for the operating sites to 362.3 million cubic meters for the proposed sites is also not statistically significant at the 95% confidence level ($P = 0.48$). The difference that is statistically significant at the 95% confidence level is the increase in the mean of the largest storage facility capacity for the sites that are closed or under care and maintenance to the proposed sites ($P = 0.05$). The ANOVA test clarifies that the difference between at least two mean largest storage facility capacities is statistically significant at better than the 99% confidence level ($P = 0.002$). The figure and calculations do not include three sites for which only the design capacity for the entire site is known. These include one site under care and maintenance (Silvana/Klondike Silver/Hinckley with storage capacity of 0.2 million cubic meters) and two proposed sites (Blackwater Gold with 462 million cubic meters and Kutcho with 3.25 million cubic meters).

Table 4a. BC Tailings Storage Database: Failure consequence categories by site status

Status	Number[1]	Highest Failure Consequence Category					
		N/A	Low	Significant	High	Very High	Extreme
Closed/C&M[2]	48	1	12	13	11	10	1
		2.1%	25.0%	27.1%	22.9%	20.8%	2.1%
Operating	18	1	2	0	5	5	5
		5.6%	11.1%	0.0%	27.8%	27.8%	27.8%
Proposed	6	1	0	0	0	4	1
		16.7%	0.0%	0.0%	0.0%	66.7%	16.7%

[1]Excludes sites for which consequence category is marked "Unclear"
[2]C&M = Care and Maintenance

Table 4b. BC Tailings Storage Database: Upstream construction and maximum heights and storages by status[1]

Status	Number[2]	Upstream Dam Present	Maximum Dam Height (m)	Maximum Current Site Storage (Mm^3)	Maximum Facility Capacity (Mm^3)
Closed/Care & Maintenance	50	14 (28.0%)	180	216.0	115.0
Operating	18	5 (27.8%)	162	1190.3	1478.0
Proposed	10	0 (0.0%)	239	N/A	1150.0

[1]Mm^3 = million cubic meters
[2]Excludes sites for which dam construction method is marked "Unclear"

The sites with tailings facilities that are either closed or under care and maintenance and the operating sites are very similar in terms of the frequency of upstream tailings dam construction. The 57 sites that are closed or under care and maintenance include 14 with dams constructed using the upstream method (see Table 1a) and an additional seven for which dam construction method is unclear (see Table 1b). The 14 sites with upstream dams that are closed or under care and maintenance include three where the highest dam failure consequence is High and four where it is Very High (see Table 1a). It is important to note that the highest dam failure consequence category at each site with an upstream dam does not necessarily refer to the upstream dam at that site. For sites for which dam construction method is unclear, the dam failure consequence category is likewise unclear, except for one in the Low consequence category (see Table 1b). The 18 operating sites include five with tailings dams constructed using the upstream method, including one, two and two where the highest dam failure consequence categories are High, Very High and Extreme, respectively. Excluding the sites for which the construction method is unknown, the frequency of upstream construction at sites that are closed or under care and maintenance (28.0%) is remarkably similar to the frequency of upstream construction at operating sites (27.8%) (see Table 4b). It is very significant that, out of the 11 proposed sites, none would involve upstream tailings dam construction, except for the Dome Mountain site, for which the dam construction method is still unclear (see Tables 2 and 4b). This pattern is consistent with the global trend in the mining industry to move away from upstream construction even in jurisdictions where upstream construction is not prohibited. (See much more discussion on this global trend in the subsection Post-Brumadinho Guidance and Data on Upstream Dams in the Appendix.)

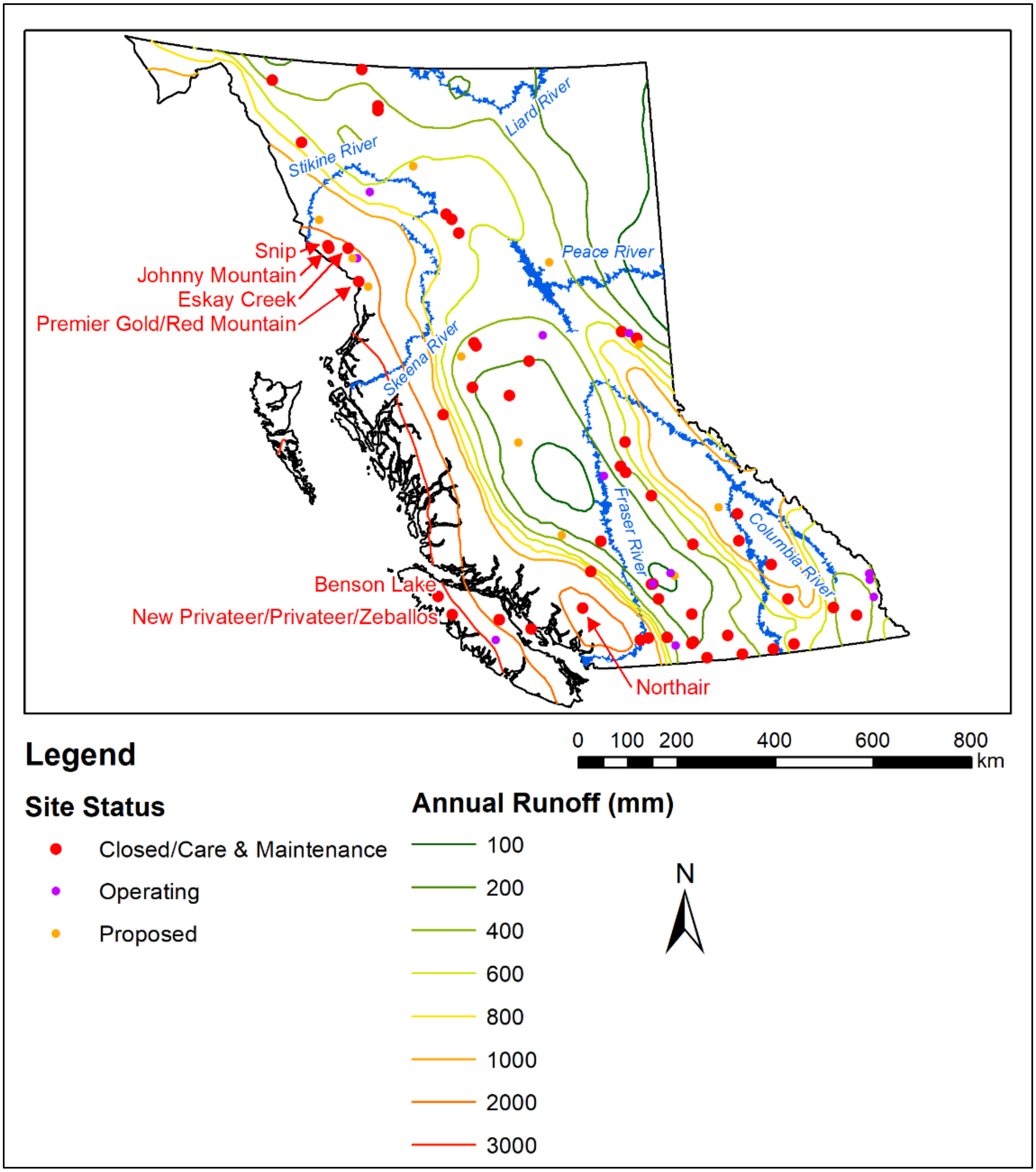

Figure 3a. A comparison of the operating status of sites containing tailings storage facilities with annual runoff in British Columbia revealed seven sites of concern. Benson Lake, Eskay Creek, Johnny Mountain, New Privateer/Privateer/Zeballos, Northair, Premier Gold/Red Mountain, and Snip are all either closed or under care and maintenance. For Benson Lake, New Privateer/Privateer/Zeballos, and Northair, dam construction method and dam failure consequence category are unclear. The annual runoff is in the range 2000-3000 mm for Northair and exceeds 3000 mm for Benson Lake and New Privateer/Privateer/Zeballos. For Eskay Creek, Johnny Mountain, Premier Gold/Red Mountain, and Snip, the annual runoff is 2000-3000 mm, and dam failure consequence categories are N/A, Significant, Very High, and Significant, respectively. Only Premier Gold/Red Mountain has an upstream dam. Annual runoff (1971-2013) from Government of Canada (2022a) and rivers from Government of British Columbia (2022a).

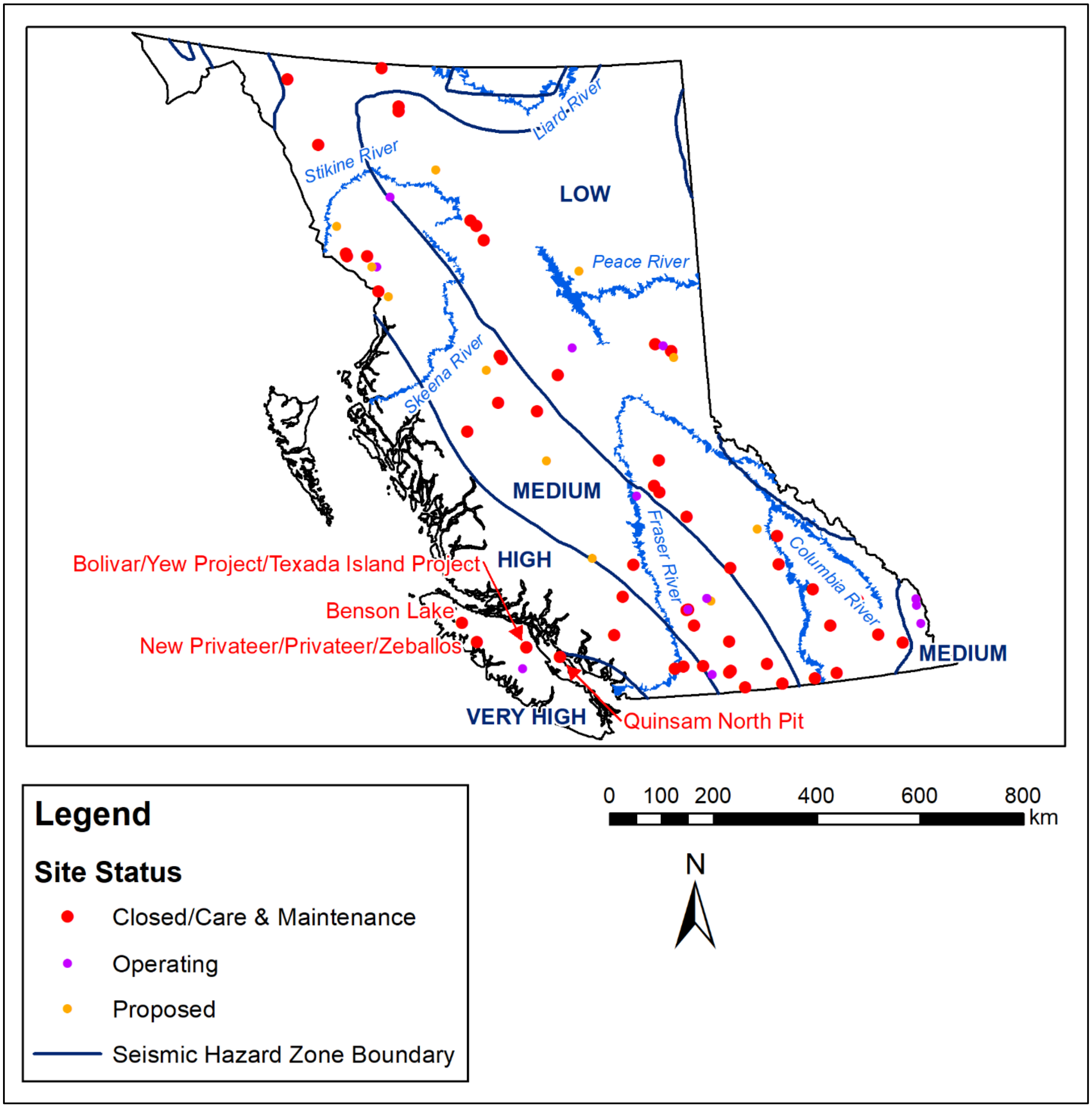

Figure 3b. A comparison of the operating status of sites containing tailings storage facilities with seismic hazard zones in British Columbia revealed four sites of concern that are located in the seismic hazard zone Very High. Benson Lake, Bolivar/Yew Project/Texada Island Project, New Privateer/Privateer/Zeballos, and Quinsam North Pit are all either closed or under care and maintenance. For Benson Lake, Bolivar/Yew Project/Texada Island Project, and New Privateer/Privateer/Zeballos, both dam construction method and dam failure consequence category are unclear. Quinsam North Pit does not have an upstream dam, but the dam failure consequence category is Very High. Seismic hazard zones from Government of Canada (2022b) and rivers from Government of British Columbia (2022a).

A comparison of the operating status of sites containing tailings storage facilities with annual runoff in British Columbia revealed seven sites of concern. These sites of concern include Benson Lake, Eskay Creek, Johnny Mountain, New Privateer/Privateer/Zeballos, Northair, Premier Gold/Red Mountain, and Snip, which are all either closed or under care and maintenance (see Fig. 3a). The annual runoff is in the range 2000-3000 mm for Eskay Creek, Johnny Mountain, Northair, and Premier Gold/Red Mountain, and exceeds 3000 mm for Benson Lake and New Privateer/Privateer/Zeballos (see Fig. 3a). A comparison of the operating status of sites containing tailings storage facilities with seismic hazard zones in British Columbia revealed four sites of concern that are located in the seismic hazard zone Very High. These sites of concern include Benson Lake, Bolivar/Yew Project/Texada Island Project, New Privateer/Privateer/Zeballos, and Quinsam North Pit, which are all either closed or under care and maintenance (see Fig. 3b). Note that Benson Lake and New Privateer/Privateer/Zeballos are sites of concern both in terms of the highest annual runoff (exceeding 3000 mm) and their location in the seismic hazard zone Very High (see Figs. 3a-b).

Comparison of Sites with Tailings Storage Facilities by Construction Method

Sites containing tailings dams constructed using the upstream method involve the additional risk factors of more severe dam failure consequence category, but not the additional risk factor of greater height, current site storage, or capacity of the largest tailings storage facility. Excluding proposed sites and sites for which consequence categories are unclear, 12 out of 19 (63.2%) sites with upstream dams also have dams in the combined High, Very High and Extreme consequence categories, while 25 out of 46 (54.3%) sites without upstream dams have dams in the combined High, Very High and Extreme consequence categories (see Table 5a). Failure consequence categories are known for all sites with upstream dams, but are unclear for three out of the 49 sites without upstream dams (excluding proposed sites and sites where dam construction is unclear). Again excluding proposed sites, the mean heights of the tallest dams at sites with upstream dams and without upstream dams are 58.4 meters and 40.3 meters, respectively, although the difference is not statistically significant at the 95% confidence level ($P = 0.13$) (see Table 5b). For sites with upstream tailings dams, the mean current site-wide storage is 53.3 million cubic meters and the mean capacity of the largest facility on site is 53.6 million cubic meters (excluding the Silvana/Klondike Silver/Hinckley site for which only the capacity across the entire site (200,000 cubic meters) is known), while, for sites without upstream dams, the mean current storage and mean capacity are 53.9 and 68.7 million cubic meters, respectively (see Table 5b). Neither of the preceding differences are statistically significant at the 95% confidence level ($P = 0.96$ for current storage and $P = 0.77$ for capacity) (see Table 5b). It should be recalled that, at each site, the tallest dam and the capacity of the largest tailings storage facility do not necessarily refer to the one or more upstream dams, and that the current site storage refers to all storage facilities, not only those with upstream dams.

A comparison of dam construction method at sites containing tailings storage facilities with annual runoff in British Columbia revealed five sites of concern. These sites of concern include Benson Lake, New Privateer/Privateer/Zeballos, and Northair, for which the construction method is unclear, as well as Myra Falls and Premier Gold/Red Mountain, which contain one or more upstream dams (see Fig. 4a). The annual runoff is in the range 2000-3000 mm for Myra Falls, Northair and Premier Gold/Red Mountain, and exceeds 3000 mm for Benson Lake and New Privateer/Privateer/Zeballos (see Fig. 4a). A comparison of dam construction method at sites containing tailings storage facilities with seismic hazard zones in British Columbia revealed four sites of concern that are located in the seismic hazard zone Very High. These sites of concern include Benson Lake, Bolivar/Yew Project/Texada Island Project, New Privateer/Privateer/Zeballos, for which the construction method is unclear, and Myra Falls, which contains at least one upstream dam (see Fig. 4b). Note again that Benson Lake and New Privateer/Privateer/Zeballos are sites of concern both in terms of the highest annual runoff (exceeding 3000 mm) and their location in the seismic hazard zone Very High (see Figs. 4a-b).

Table 5a. BC Tailings Storage Database: Failure consequence categories by dam construction method[1]

Upstream Dam Present	Number[2]	Highest Failure Consequence Category					
		N/A	Low	Significant	High	Very High	Extreme
Yes	19	0	3 (15.8%)	4 (21.1%)	4 (21.1%)	6 (31.6%)	2 (10.5%)
No	46	2 (4.3%)	10 (21.7%)	9 (19.6%)	12 (26.1%)	9 (19.6%)	4 (8.7%)

[1]Excludes proposed sites
[2]Excludes sites for which consequence category is marked "Unclear"

Table 5b. BC Tailings Storage Database: Height and storage by dam construction method[1,2]

Upstream Dam Present	Mean Maximum Dam Height (m)	Mean Current Site Storage (Mm^3)	Mean Largest Facility Capacity (Mm^3)
Yes	58.4	53.3	53.6[3]
No	40.3[4]	53.9[5]	68.7[6]

[1]Excludes proposed sites
[2]Mm^3 = million cubic meters
[3]Excludes Silvana/Klondike Silver/Hinckley site for which only the capacity across the entire site (200,000 cubic meters) is known
[4]Difference between Yes and No is not statistically significant at the 95% confidence level ($P = 0.13$)
[5]Difference between Yes and No is not statistically significant at the 95% confidence level ($P = 0.96$)
[6]Difference between Yes and No is not statistically significant at the 95% confidence level ($P = 0.77$)

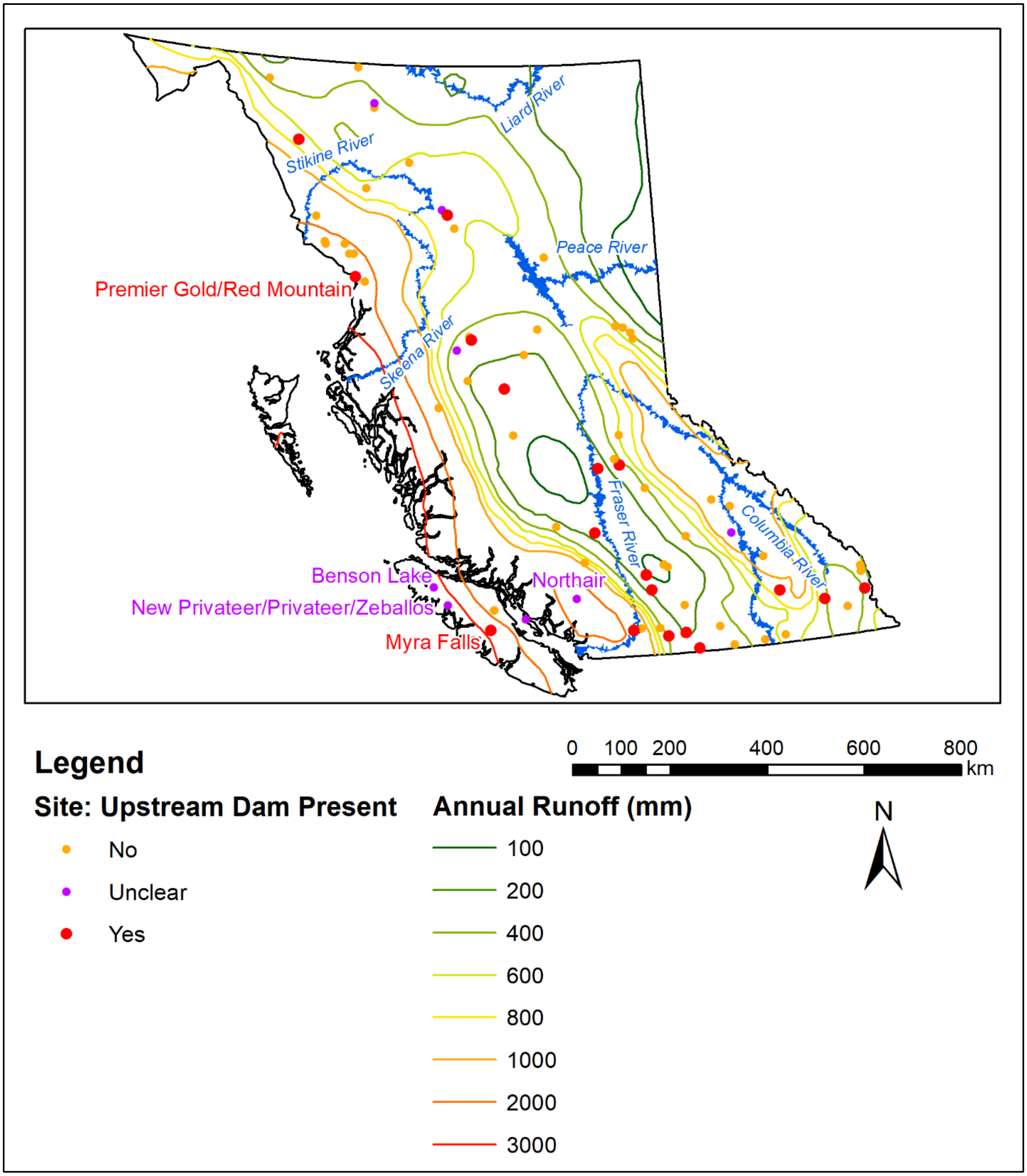

Figure 4a. A comparison of dam construction method at sites containing tailings storage facilities with annual runoff in British Columbia revealed five sites of concern. Benson Lake, New Privateer/Privateer/Zeballos, and Northair are all either closed or under care and maintenance, with both dam construction method and dam failure consequence category unclear. The annual runoff is in the range 2000-3000 mm for Northair and exceeds 3000 mm for Benson Lake and New Privateer/Privateer/Zeballos. Premier Gold/Red Mountain and Myra Falls are both operating sites with upstream dams with annual runoff in the range 2000-3000 mm. The highest dam failure consequence categories for Premier Gold/Red Mountain and Myra Falls are Very High and High, respectively. Annual runoff (1971-2013) from Government of Canada (2022a) and rivers from Government of British Columbia (2022a).

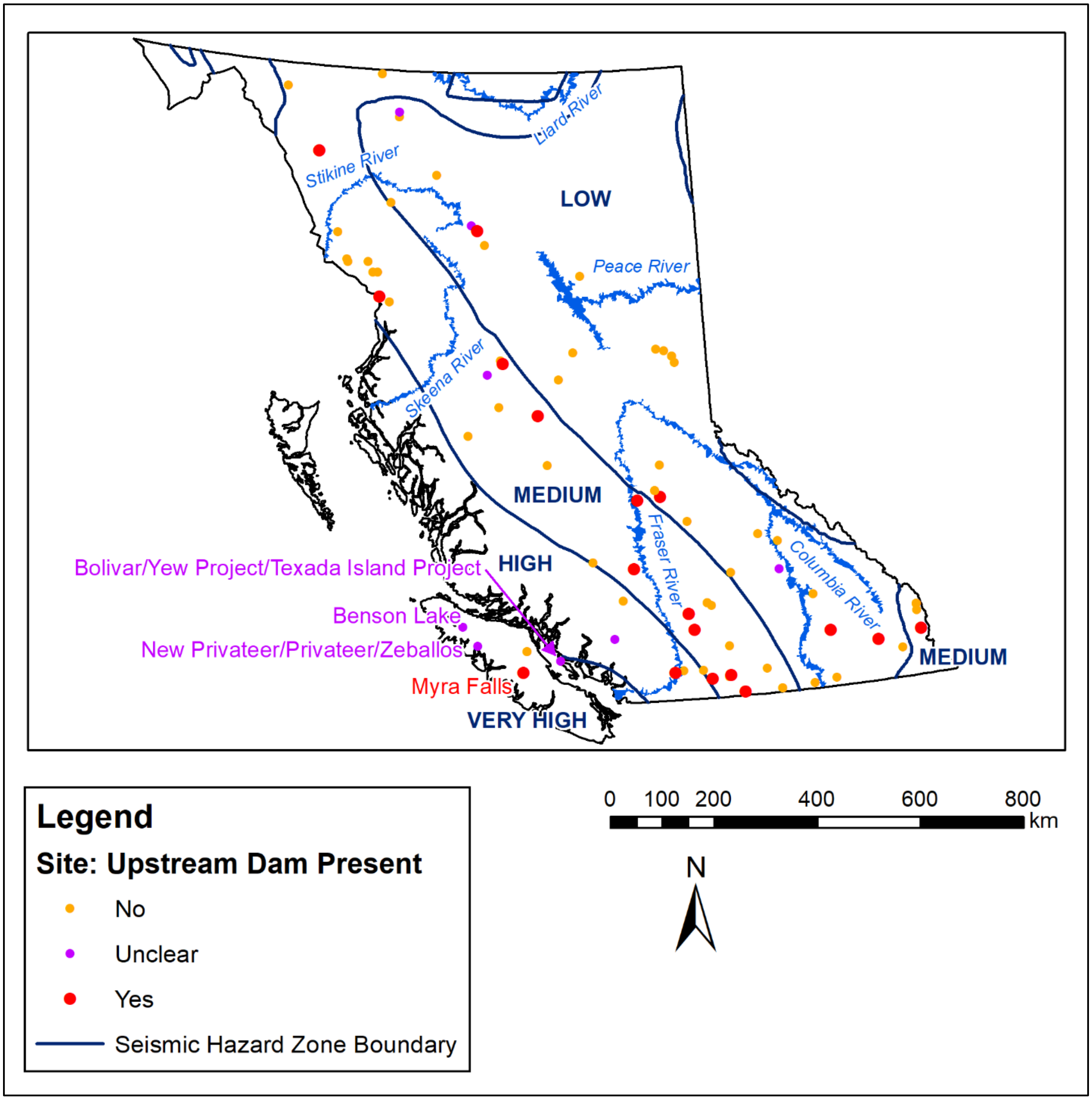

Figure 4b. A comparison of dam construction method at sites containing tailings storage facilities with seismic hazard zones in British Columbia revealed four sites of concern. Benson Lake, Bolivar/Yew Project/Texada Island Project, and New Privateer/Privateer/Zeballos are all either closed or under care and maintenance. For all three sites, dam construction method is unclear, dam failure consequence category is unclear, and the seismic hazard zone is Very High. Myra Falls is an operating site with one or more upstream dams in seismic hazard zone Very High and with highest dam failure consequence category High. Seismic hazard zones from Government of Canada (2022b) and rivers from Government of British Columbia (2022a).

Comparison of Sites with Tailings Storage Facilities by Dam Failure Consequence

It is most instructive to examine the dam failure consequence category Extreme (see Table 3). The seven sites containing tailings dams for which consequences would be Extreme in the event of failure (potential loss of more than 100 lives) include one closed site (Brenda), five operating sites (Copper Mountain, Gibraltar – TSF, HVC – Highland, New Afton – HATSF, New Afton – NATSF), and one proposed site (KSM) (see Table 3). The sites in this failure consequence category include two operating sites with upstream dams (Copper Mountain and Gibraltar – TSF). In both cases, the tailings storage facility with the upstream dam is the same as the tailings storage facility with the Extreme consequence rating, which is a disturbing combination of unacceptable probability of failure and unacceptable consequences of failure. The placement of the proposed KSM tailings facility in the failure consequence category Extreme certainly seems reasonable, considering its height of 239 meters and capacity of 1150 million cubic meters. The proposed KSM tailings storage facility will be considered further in the subsection Sites with Tailings Storage Facilities of Concern and in the Recommendations.

A comparison of highest dam failure consequence category at sites containing tailings storage facilities with annual runoff in British Columbia revealed seven sites of concern. For annual runoff in the range 2000-3000 mm, KSM is in the consequence category Extreme, Premier Gold/Red Mountain and Red Mountain Underground Gold are in the consequence category Very High, Myra Falls is in the consequence category High, and the consequence category is unclear for Northair. For annual runoff exceeding 3000 mm, dam failure consequence category is unclear for Benson Lake and New Privateer/Privateer/Zeballos (see Fig. 5a). A comparison of dam failure consequence category at sites containing tailings storage facilities with seismic hazard zones in British Columbia revealed five sites of concern that are located in the seismic hazard zone Very High. These sites of concern include Quinsam North Pit for which the highest dam consequence category is Very High, Myra Falls for which the highest dam consequence category is High, and Benson Lake, Bolivar/Yew Project/Texada Island Project and New Privateer/Privateer/Zeballos for which the dam consequence category is unclear (see Fig. 5b). Note again that Benson Lake and New Privateer/Privateer/Zeballos are sites of concern both in terms of the highest annual runoff (exceeding 3000 mm) and their location in the seismic hazard zone Very High (see Figs. 5a-b).

Sites with Tailings Storage Facilities of Concern

A compilation of the previous three subsections reveals 12 sites containing tailings storage facilities of concern. These 12 sites include nine that are either closed or in care and maintenance (Benson Lake, Bolivar/Yew Project/Texada Island Project, Eskay Creek, Johnny Mountain, New Privateer/Privateer/Zeballos, Northair, Premier Gold/Red Mountain, Quinsam North Pit, Snip), one operating site (Myra Falls), and two proposed sites (KSM, Red Mountain Underground Gold) (see Tables 6a-c). The existence of two proposed sites (KSM and Red Mountain Underground Gold) within the list of sites with tailings storage facilities of concern cannot be overemphasized. Out of all options for stabilizing tailings dams at risk of failure or for safeguarding downstream communities, denying a permit for a facility that does not yet exist is by far the least expensive.

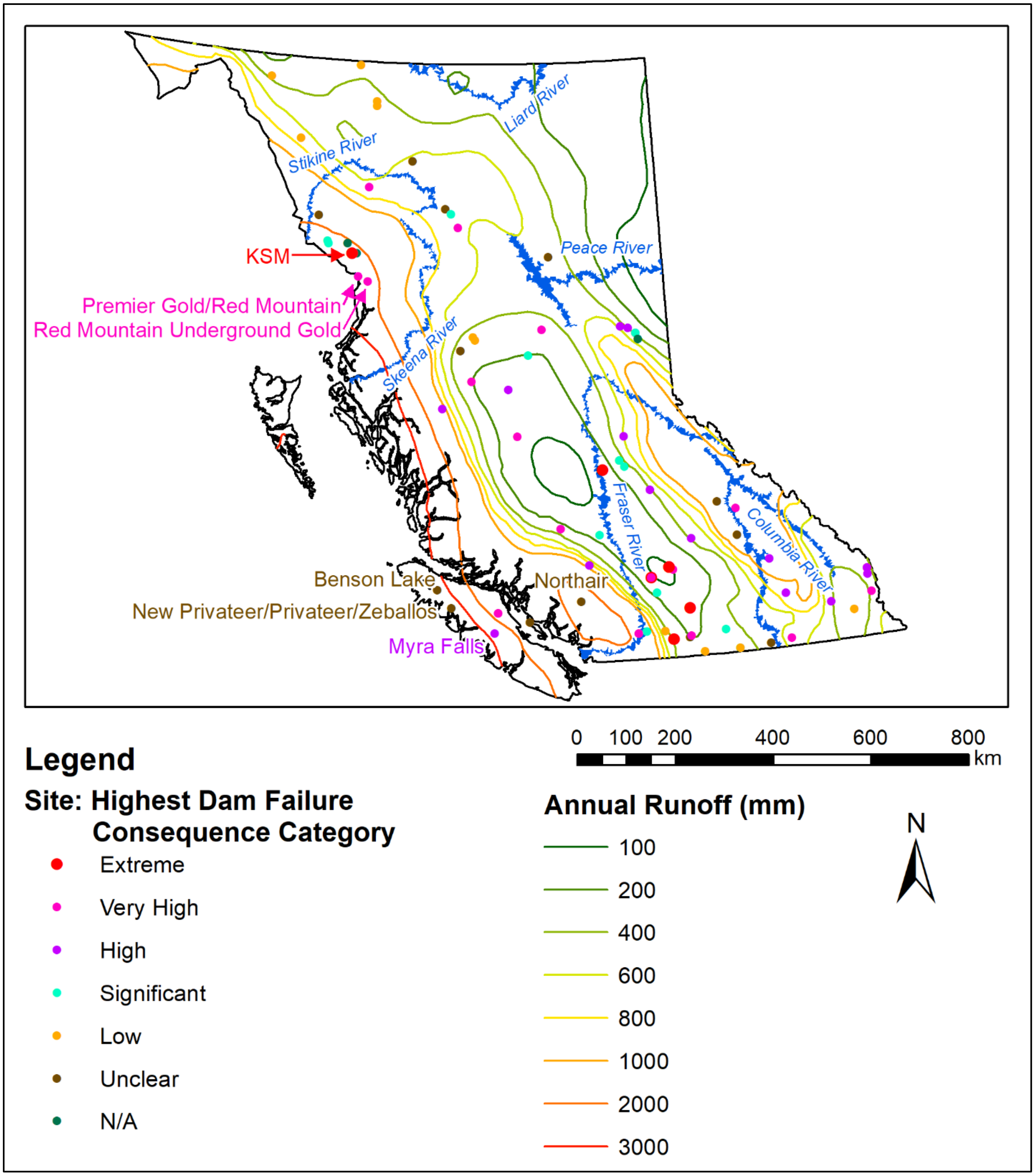

Figure 5a. A comparison of highest dam failure consequence category at sites containing tailings storage facilities with annual runoff in British Columbia revealed seven sites of concern. Benson Lake, New Privateer/Privateer/Zeballos, Northair, and Premier Gold/Red Mountain are all either closed or under care and maintenance, while KSM and Red Mountain Underground Gold are proposed sites. Dam failure consequence categories are unclear for Benson Lake, New Privateer/Privateer/Zeballos and Northair, Extreme for KSM, Very High for Premier Gold/Red Mountain and Red Mountain Underground Gold, and High for Myra Falls. Annual runoff (1971-2013) from Government of Canada (2022a) and rivers from Government of British Columbia (2022a).

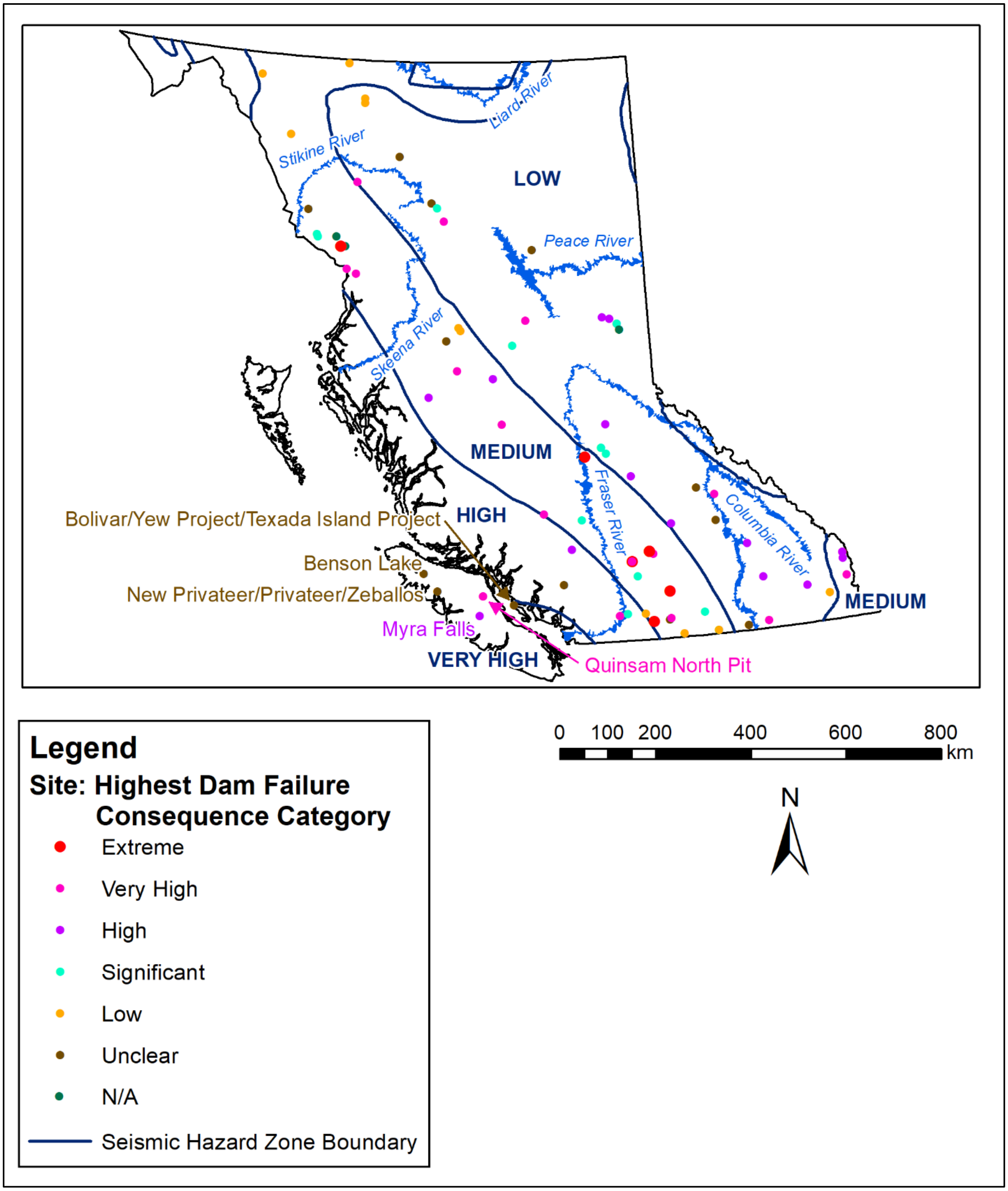

Figure 5b. There are five sites of concern in the seismic hazard zone Very High. Benson Lake, Bolivar/Yew Project/Texada Island Project, New Privateer/Privateer/Zeballos, and Quinsam North Pit are all either closed or under care and maintenance, while Myra Falls is operating. For Benson Lake, Bolivar/Yew Project/Texada Island Project, and New Privateer/Privateer/Zeballos, both dam construction method and dam failure consequence category are unclear. Quinsam North Pit does not have an upstream dam, but the highest dam failure consequence category is Very High. Myra Falls does have an upstream dam, and the highest failure consequence category is High. Seismic hazard zones from Government of Canada (2022b) and rivers from Government of British Columbia (2022a).

Table 6a. Sites with tailings storage facilities of concern: Annual runoff = 2000-3000 mm

Mine	Upstream Dam Present	Status[1]	Highest Consequence Category
Eskay Creek	No	Closed/C&M	N/A
Johnny Mountain	No	Closed/C&M	Significant
KSM	No	Proposed	Extreme
Myra Falls	Yes	Operating	High
Northair	Unclear	Closed/C&M	Unclear
Premier Gold/Red Mountain	Yes	Closed/C&M	Very High
Red Mountain Underground Gold	No	Proposed	Very High
Snip	No	Closed/C&M	Significant

[1]C&M = Care & Maintenance

Table 6b. Sites with tailings storage facilities of concern: Annual runoff > 3000 mm

Mine	Upstream Dam Present	Status[1]	Highest Consequence Category
Benson Lake	Unclear	Closed/C&M	Unclear
New Privateer/Privateer/Zeballos	Unclear	Closed/C&M	Unclear

[1]C&M = Care & Maintenance

Table 6c. Sites with tailings storage facilities of concern: Seismic hazard zone = Very High

Mine	Upstream Dam Present	Status[1]	Highest Consequence Category
Benson Lake	Unclear	Closed/C&M	Unclear
Bolivar/Yew Project/Texada Island Project	Unclear	Closed/C&M	Unclear
Myra Falls	Yes	Operating	High
New Privateer/Privateer/Zeballos	Unclear	Closed/C&M	Unclear
Quinsam North Pit	No	Closed/C&M	Very High

[1]C&M = Care & Maintenance

Potential Impacts of Tailings Dam Failures on Salmon and Communities

A comparison of entries in the BC Tailings Storage Database with maps of municipal boundaries and salmon habitat shows considerable threat to both communities and ecosystems. In this context, “threat” refers to the consequences of tailings dam failure, rather than to the probability of failure. Out of 86 sites containing tailings storage facilities, 54 are located directly within salmon habitat (see Fig. 6). In fact, any tailings storage facility located within the watersheds of the Fraser River (see Fig. 7), Skeena River, or Stikine River has the potential to impact salmon habitat in the event of failure.

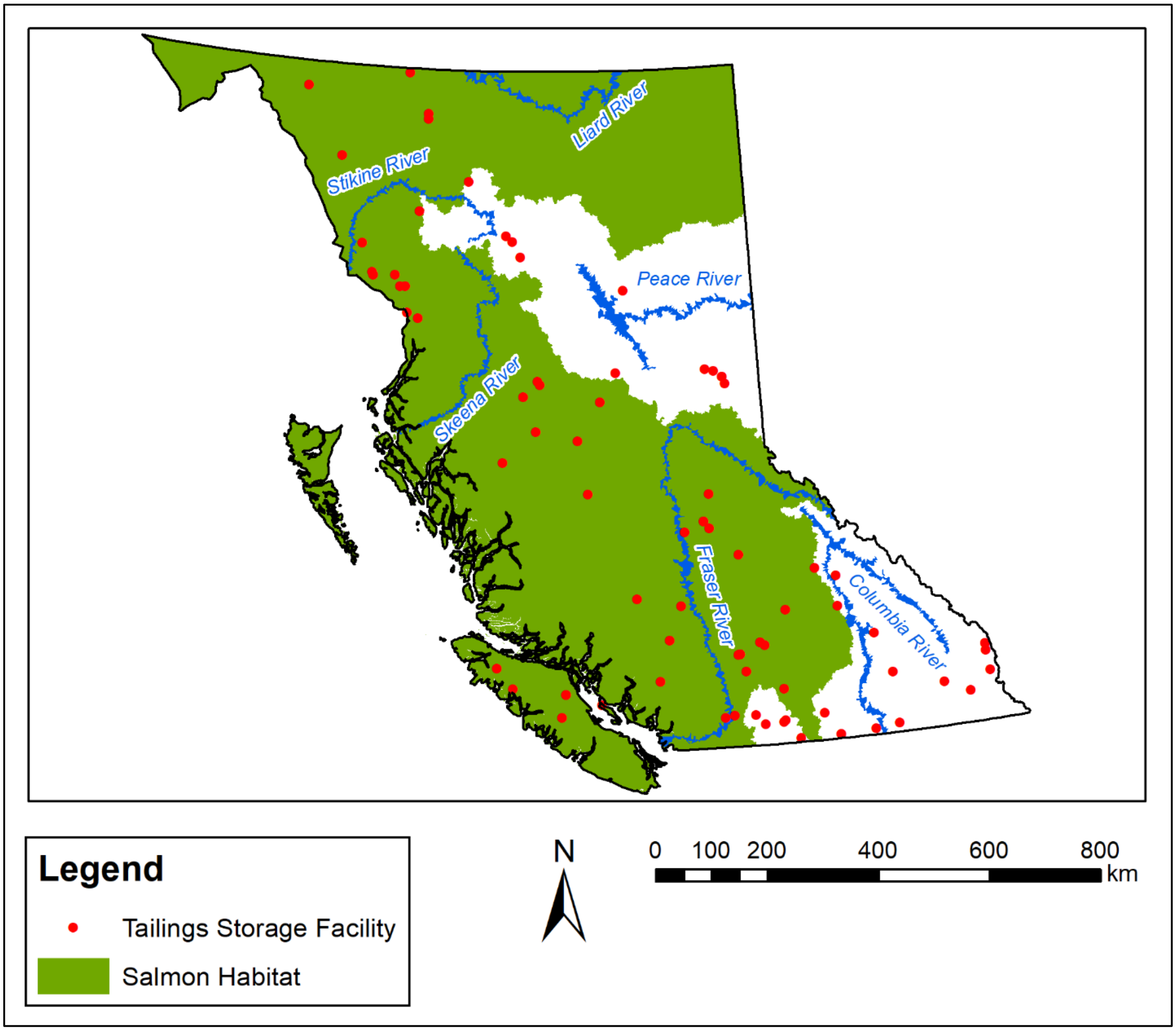

Figure 6. A comparison of salmon habitat with sites containing tailings storage facilities in British Columbia reveals considerable threat to salmon. In fact, out of 86 sites, 54 are located within salmon habitat. Rivers from Government of British Columbia (2022a) and salmon habitat from Government of British Columbia (2022b).

Out of the 72 sites for which the dam failure consequence category is known, 16 are in the High category, 19 are in the Very High category, and 7 are in the Extreme category (see Table 4a). Based on potential losses of 1-10 lives in the High category, 11-100 lives in the Very High category, and more than 100 lives in the Extreme category (see Fig. 1), 932-2767 lives are at risk from tailings dam failure in British Columbia, assuming that 101 lives would be at risk in the event of failure of a dam in consequence category Extreme. The upper bound (2767 lives) is certainly low and could be even several orders of magnitude too low for the following reasons:

1) There are an additional 14 sites for which the dam failure consequence category is unknown.
2) Each of the 72 sites for which the dam failure consequence category is known could have multiple tailings dams or tailings storage facilities, any one of which could fail.
3) The potential loss of lives in the event of failure of a dam in the consequence category Extreme is unbounded, and could be far greater than 101.

With regard to the second reason, it should be noted that, because major causes of tailings dam failures are earthquakes and overtopping by floods, tailings dam failures are not necessarily independent. Thus, it is distinctly possible that the same precipitation or seismic event could result in multiple tailings dam failures at a single site, especially if it is a closed site that has not been receiving adequate monitoring, inspection and maintenance.

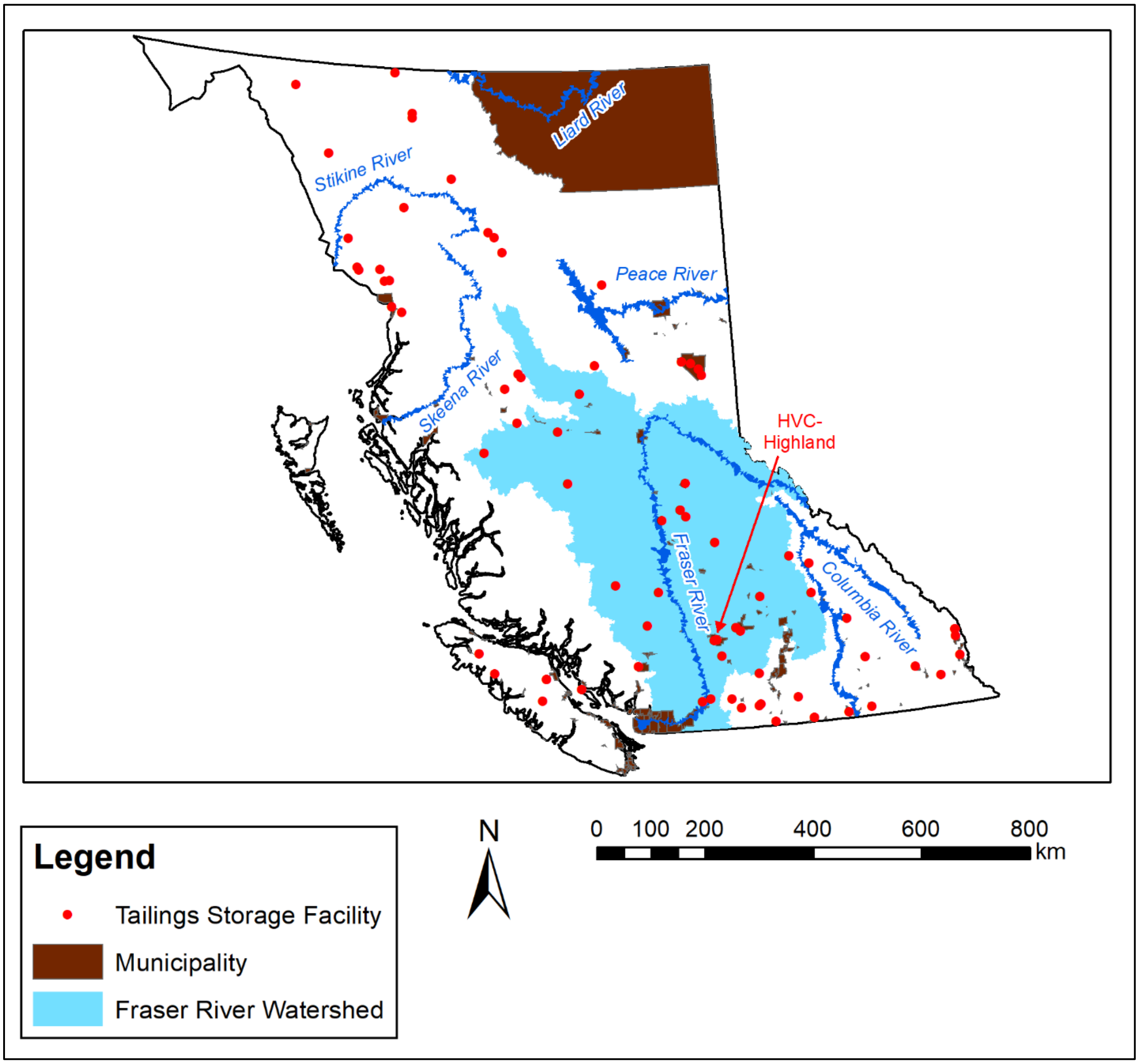

Figure 7. A comparison of municipal boundaries with sites containing tailings storage facilities in British Columbia reveals considerable threat to downstream communities, especially along the lower Fraser River. A partial list of potentially impacted cities along the lower Fraser River includes Abbotsford (population 151,683), Burnaby (population 202,799), Chilliwack (population 77,000), Coquitlam (population 114,565), Delta (population 101,668), Langley (population 23,606), Maple Ridge (population 70,000), Mission, North Vancouver (population 48,000), Pitt Meadows (population 17,410), Port Coquitlam, Port Moody (population 27,512), Richmond (population 182,000), Surrey (population 394,976), Vancouver (population 600,000), and White Rock (population 66,450). Rivers from Government of British Columbia (2022a), municipal boundaries from Government of British Columbia (2022c), and watersheds from Government of British Columbia (2022d).

The many municipalities along the lower Fraser River appear particularly vulnerable to tailings dam failure at any of the 27 existing and proposed sites containing tailings storage facilities within the watershed of the Fraser River (see Fig. 7). It should be noted that potential loss of life is not the only possible impact on a community. Unless the spilled tailings were contained within a lake or reservoir (as happened after the tailings dam failure at the Mount Polley mine), a tailings dam failure at any of the 27 sites would eventually result in the flow of the toxic tailings through the municipalities along the Fraser River. As a single example, if the failure of the largest tailings storage facility at the HVC – Highland site released all stored tailings at the maximum capacity, nearly 1500 million cubic meters of toxic tailings (see Table 3) would flow through the cities along the lower Fraser River (see Fig. 7). A partial list of potentially impacted cities along the lower Fraser River includes Abbotsford (population 151,683), Burnaby (population 202,799), Chilliwack (population 77,000), Coquitlam (population 114,565), Delta (population 101,668), Langley (population 23,606), Maple Ridge (population 70,000), Mission, North Vancouver (population 48,000), Pitt Meadows (population 17,410), Port Coquitlam, Port Moody (population 27,512), Richmond (population 182,000), Surrey (population 394,976), Vancouver (population 600,000), and White Rock (population 66,450) (World Population Review, 2022).

DISCUSSION

It has already been noted that, out of the 11 proposed sites with tailings storage facilities, four have dams in the failure consequence category Very High, one has one or more dams in the failure consequence category Extreme, one has failure consequence category N/A, and the rest are not yet known (see Tables 2 and 4a). The lack of any proposed sites where tailings dams are all in the failure consequence categories Low, Significant or High suggests that it is no longer economically possible to construct a tailings storage facility for which failure would result in the potential loss of fewer than 10 lives. The only exception seems to be the Roman Coal Mine/Trend-Roman site, for which the dam failure consequence is labeled N/A (see Table 2). The economic non-feasibility of constructing new tailings storage facilities that would not endanger the public in British Columbia demands careful consideration.

Mining is always a balance between risks and benefits. However, in the case of tailings storage facilities, for which failure can be disastrous, it is generally agreed that the safety of mineworkers and the downstream communities come first. According to the expert panel that reviewed the disaster at the Mount Polley mine, "Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor … Future permit applications for a new TSF [Tailings Storage Facility] should be based on a bankable feasibility that would have considered all technical, environmental, social and economic aspects of the project in sufficient detail to support an investment decision, which might have an accuracy of ±10%–15%. More explicitly, it should contain the following: … b. Detailed cost/benefit analyses of BAT [Best Available Technology] tailings and closure options so that economic effects can be understood, recognizing that the results of the cost/benefit analyses should not supersede BAT safety considerations" (Independent Expert Engineering Investigation and Review Panel, 2015b). Roche at al. (2017) agreed and even quoted from the Mount Polley report in writing, "The approach to tailings storage facilities must place safety first by making environmental and human safety a priority in management actions and on-the-ground operations. Regulators, industry and communities should adopt a shared zero-failure objective to tailings storage facilities where ‘safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor.’” The mining industry has also agreed that, in terms of tailings storage, safety comes first. According to ICMM-UNEP-PRI (2020), “The Global Industry Standard on Tailings Management (herein ‘the Standard’) strives to achieve the ultimate goal of zero harm to people and the environment with zero tolerance for human fatality.” The same high standard of protection for workers and the public is upheld in the water-retention dam industry. According to the U.S. Army Corps of Engineers, “A key mission of the USACE dam safety program is to achieve an equitable and reasonably low level of risk to the public from its dams. USACE executes its project purposes guided by its commitment and responsibility to public safety. Since ‘Life Safety is Paramount,’ it is not appropriate to refer to balancing or trading off public safety with other project benefits. Instead, it is after tolerable risk guidelines are met that other purposes and objectives will be considered” (USACE, 2014).

The important point is that there are two possible interpretations of the predominance of high-risk tailings dams among the proposed sites (see Table 2). The first interpretation is that safety has, in fact, not dominated over economic considerations, and that the locations for new tailings storage facilities are being chosen at locations that unnecessarily endanger the public welfare. If this is the case, the regulatory agencies in British Columbia need to carefully consider the wisdom of the locations of the tailings storage facilities at the proposed sites. The second interpretation is that the chosen locations truly are the safest possible for a given mining project. In other words, the mining project, as an entirety, would not be economically possible if those particular locations were not chosen. This last possibility does not bode well for the future safety of the inhabitants of British Columbia because it implies that new relatively safe locations for tailings storage facilities will cease to exist as ore deposits are exhausted and as the grades of the remaining ore deposits continue to drop.

It is worth noting that some of the proposed sites would include tailings storage facilities that would be among the tallest in the world. Based on the Global Tailings Portal (Franks et al., 2021; GRID-Arendal, 2022), at present, the tallest tailings dam in the world is the Linga dam at the Freeport Cerro Verde mine in Peru with a height of 265 meters. By comparison, with a height of 239 meters, the tallest tailings dam at the KSM site (see Table 2) would be the seventh tallest tailings dam in the world and far taller than the tallest tailings dam in Canada, which has a height of 180 meters and is at the Kemess South/Kemess Underground (KUG) site (GRID-Arendal, 2022) (see Table 4b). There is currently another proposal (Copper Mountain Mining Corporation, 2020; Klohn Crippen Berger, 2020) to raise the heights of the East Dam and West Dam at the operating Copper Mountain site to 259.5 meters and 251.5 meters, which would make the East Dam and West Dam the second and third tallest tailings dams in the world.

The designation N/A as a dam failure consequence category (see Table 4a) also requires careful consideration. In addition to the proposed site Roman Coal Mine/Trend-Roman, two other sites with the dam failure consequence category N/A are the operating site Brucejack and the site Eskay Creek, which is under care and maintenance. Although N/A is not a dam failure consequence category of the Canadian Dam Association (2013) (see Fig. 1), regulatory agencies have used the designation N/A to indicate the absence of a dam, for example, when the tailings are disposed into a lake or backfilled into an exhausted open pit. In those cases, careful consideration should be given as to whether there truly are no credible failure modes, such as no physically possible way that the tailings or the tailings pond could spill onto the surface, even in response to the Probable Maximum Flood that takes into account future climate change. The proposed site Roman Coal Mine/Trend-Roman is the most important in this respect, since as noted in the discussion of the two proposed sites (KSM, Red Mountain Underground Gold) that are identified as containing tailings storage facilities of concern, denying a permit for a facility that does not yet exist is by far the least expensive option for safeguarding downstream communities.

Along the above lines, it is crucial that the creators of the BC Tailings Storage Database retain in the database all sites with the present statuses of Closed or Care & Maintenance until such time as it has been convincingly demonstrated that the tailings dams at those sites have no remaining credible failure modes. In this respect, it is not enough to claim that the sites have been "reclaimed" or "remediated." In principle, tailings storage facilities can be reshaped to resemble natural landforms, which is not the same concept as the elimination of all credible failure modes. It is common enough for natural landforms to fail by landsliding (especially in British Columbia), although without the release of the potentially millions of metric tons of toxic tailings that would occur if the "landform" were only a reshaped tailings storage facility. It should be recalled from the section Summary of Risk Factors for Tailings Dam Failure that failure should be regarded as inevitable unless one of the following conditions holds:

1) There are no credible failure modes, or
2) Monitoring, inspection, and maintenance is being carried out in perpetuity.

It should be further recalled that the lack of credible modes involves an unusual set of circumstances and that the realism of perpetual care has been seriously questioned, especially within the mining industry.

Although this report has revealed considerable risk from the many sites with tailings storage facilities in British Columbia, the risk has probably been underestimated. The BC Tailings Storage Database counts tailings dams as "upstream" only if that exact terminology is used in mining company or government documents. The exception is that tailings dams that include upstream raises (Copper Mountain and Mount Polley) are properly counted as upstream dams in the BC Tailings Storage Database, even if some raises are centerline. By contrast, the Global Tailings Portal counts tailings facilities with more than one type of raise (some combination of upstream, downstream and centerline raises) as "hybrid" dams (Franks et al., 2021; GRID-Arendal, 2022).

On the other hand, the BC Tailings Storage Database does not count tailings dams as "upstream" if the alternative terminology "modified centerline" is used in mining company or government documents. For example, the mining company Centerra Gold (2022) lists the closed Kemess South/Kemess Underground (KUG) tailings storage facility (with a height of 180 meters) as constructed by the "modified centerline" method (see Fig. 8), and this site is listed as a site with no upstream tailings dams in the BC Tailings Storage Database. As explained in the subsection Modified Centerline and Hybrid Tailings Dams in the Appendix, the phrase "modified centerline" is non-standard terminology because the dam is still constructed on top of the uncompacted tailings (in the manner of an upstream dam). The correct terminology is "modified upstream," which has been confirmed by the International Commission on Large Dams (ICOLD), so that the number of sites containing upstream tailings dams in the BC Tailings Storage Database has been undercounted (ICOLD, 2021; see Fig. A22). Although the Global Tailings Portal includes "Modified Centreline" dam as a choice for Raise Type, that Raise Type corresponds to the Raise Category "Hybrid," rather than the Raise Category "Centreline" (Franks et al., 2021). Thus, the user of the portal is able to decide for him or herself whether to regard modified centerline dams as a type of upstream or non-upstream dam.

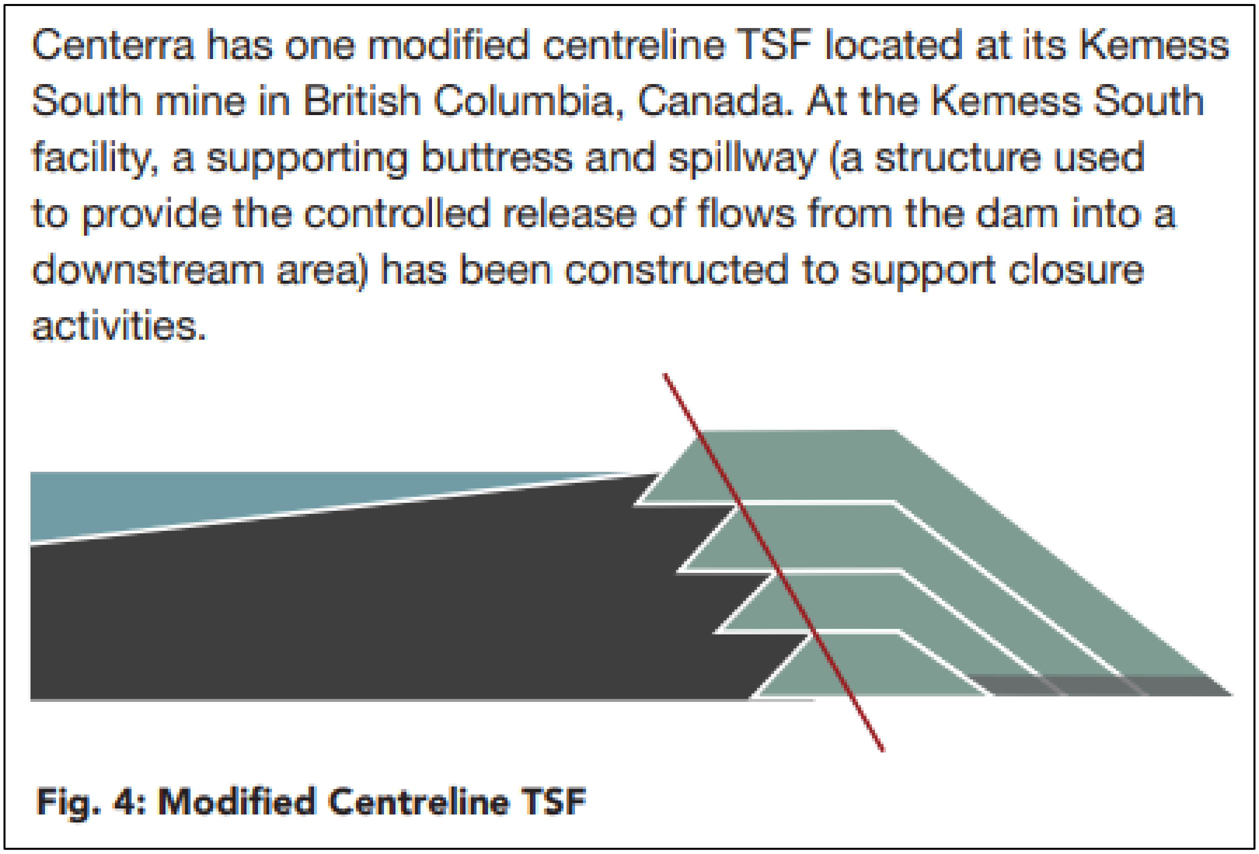

Figure 8. Although Centerra Gold (2022) claims that the tailings dam at the Kemess South facility (with a height of 180 meters) was constructed using the "modified centerline" method, the construction is actually a variation on the upstream method, since the dikes are constructed on top of the uncompacted tailings (compare with Figs. A2a and A2c). In fact, ICOLD (2021) refers to the construction method as "modified upstream" (see Fig. A22). Figure from Centerra Gold (2022).

Taking full account of all "modified centerline" dams and counting them as "upstream" dams has the power to substantially increase the perceived risk of failure of tailings dams in British Columbia. For example, if the single example of the Kemess South/Kemess Underground (KUG) were moved from the non-upstream to the upstream category, the mean height of the tallest dams at sites with upstream dams would increase to 64.5 meters, the mean height of the tallest dams at sites without upstream dams would decrease to 37.0 meters, and the difference would be statistically significant at better than the 95% confidence level ($P = 0.035$) (compare with Table 5b). This single adjustment would reverse the previous statement in this report that "sites containing tailings dams constructed using the upstream method [do not] involve … the additional risk factors of greater height" because sites with upstream dams would be shown to have a tallest dam that is taller than the tallest dam at sites without upstream dams. It should be recalled that the tallest dam at a site is not necessarily an upstream dam. However, the combination of both tall dams and upstream dams at a single site certainly raises the risk profile of a site, even if the upstream dams are shorter. Although, as explained earlier, taller dams do not necessarily have a higher probability of failure, the consequences of failure would certainly be more severe. In the case of the 11 proposed sites containing tailings storage facilities, for which there are no upstream dams, it is particularly important to know whether any dams at these sites are being labeled as "modified centerline."

Tailings storage facilities constructed on top of existing tailings are another category that deserves special consideration. Even if these are not upstream tailings dams, they can still retain some "upstream character" if the underlying tailings were not properly compacted. In that sense, if the underlying existing tailings underwent liquefaction (for example, in response to an earthquake), even if the new tailings dam temporarily maintained its structural integrity, it could fail simply by falling into or sliding over the underlying liquefied tailings. Two examples in British Columbia are the tailings dam at the Table Mountain site (see Fig. 9a) and the QR Mine – TSF (see Fig. 9b). The tailings dam at the Table Mountain site is a single-stage dam constructed on top of and incorporating an existing dam with impounded tailings (see Fig. 9a). The cross-section of QR Mine – TSF shows progressive dam raises in the downstream direction, indicating that it is a downstream dam (see Fig. 9b). However, the tailings dam retains some "upstream character" because it includes an upstream embankment of "sandy till" that was placed on top of "existing waste and/or tailings" (see Fig. 9b). The BC Tailings Storage Database properly does not count either the Table Mountain tailings dam or QR Mine – TSF as upstream dams (see Tables 1a-c). However, it would be informative, and potentially useful for a more accurate evaluation of the risk of tailings dam failure in British Columbia if a future version of the BC Tailings Storage Database indicated whether any portion of a tailings dam had been constructed on top of previously-existing tailings.

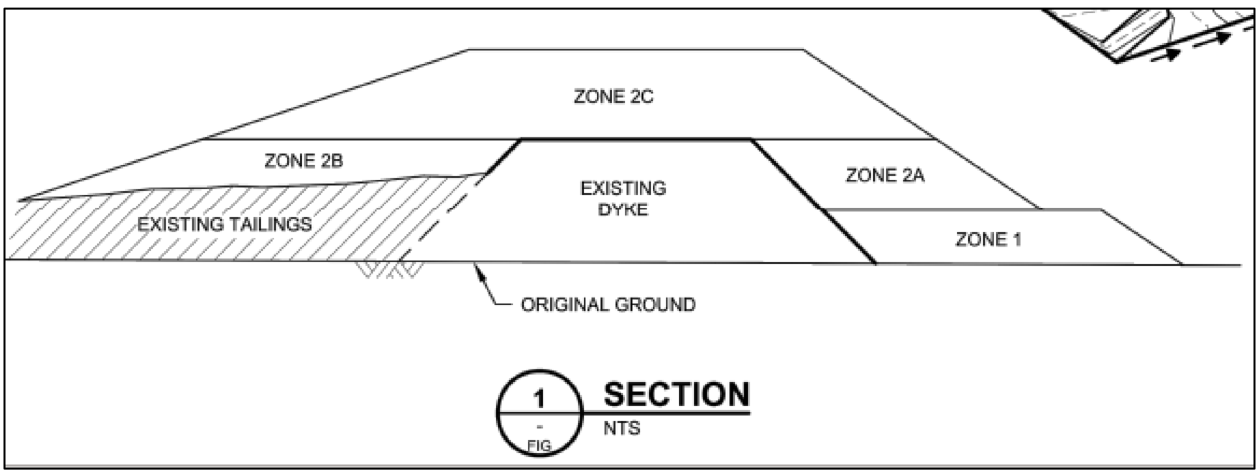

Figure 9a. The tailings dam at the Table Mountain site is a single-stage dam constructed on top of and incorporating an existing dam with impounded tailings. The BC Tailings Storage Database properly does not count the Table Mountain tailings dam as an upstream dam (see Tables 1a-c). However, the tailings dam retains some "upstream character" because it is constructed on top of existing tailings and it is not known whether those existing tailings were ever properly compacted. In that sense, if the underlying existing tailings underwent liquefaction (for example, in response to an earthquake), even if the new tailings dam temporarily maintained its structural integrity, it could fail simply by falling into or sliding over the underlying liquefied tailings. The accompanying text (Tetra Tech Canada, 2017) does not clarify the meanings of the zones, which do not use standard nomenclature (compare with Fell et al., 2015). Portion of figure from Tetra Tech Canada (2017).

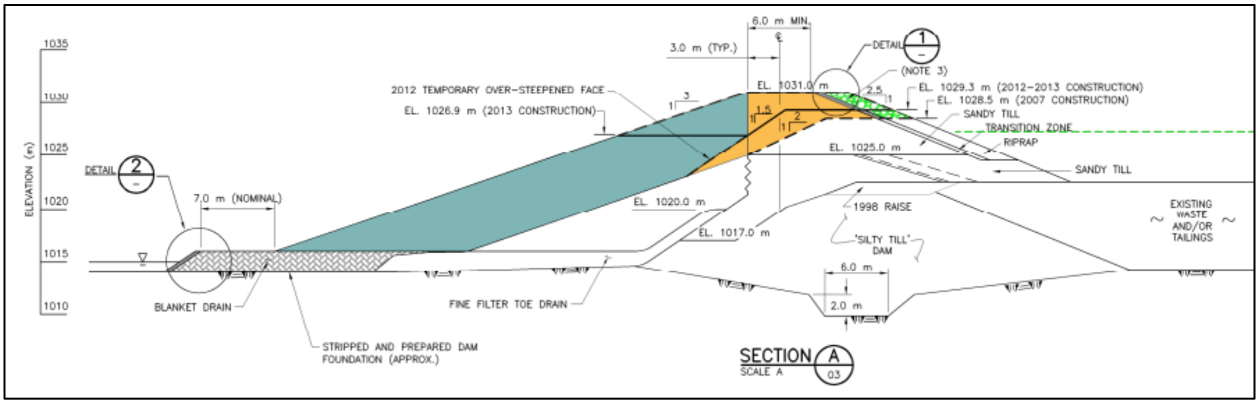

Figure 9b. The above cross-section of QR Mine – TSF shows progressive dam raises in the downstream direction, indicating that it is a downstream dam. Thus, the BC Tailings Storage Database properly does not count the QR Mine – TSF as having an upstream dam (see Tables 1a-c). However, the tailings dam retains some "upstream character" because it includes an upstream embankment of "sandy till" that was placed on top of "existing waste and/or tailings" and it is not known whether those existing tailings were ever properly compacted. In that sense, if the underlying existing tailings underwent liquefaction (for example, in response to an earthquake), even if the tailings dam temporarily maintained its structural integrity, it could fail simply by falling into or sliding over the underlying liquefied tailings. Portion of figure from Klohn Crippen Berger (2021).

CONCLUSIONS

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

1) The 86 sites containing tailings storage facilities in the British Columbia Existing and Future Tailings Storage Database include 57 sites that are closed or under care and maintenance, 18 operating sites, and 11 proposed sites. The 57 sites that are closed or under care and maintenance include 14 with tailings dams constructed using the upstream method and an additional seven sites for which tailings dam construction method is unclear. The 14 sites with upstream dams that are closed or under care and maintenance include three where the highest dam failure consequence is High and four where it is Very High. For sites for which dam construction method is unclear, the dam failure consequence category is likewise unclear, except for one in the Low consequence category. The 18 operating sites include five with tailings dams constructed using the upstream method, including one, two and two where the highest dam failure consequence categories are High, Very High and Extreme, respectively.
2) The seven sites with tailings dams in the failure consequence category Extreme include one closed site, five operating sites, and one proposed site.
3) There are no proposed upstream tailings dams, except for one site for which dam construction method is still unclear, which is consistent with the global trend on the part of the mining industry to move away from upstream construction, even where it is not prohibited.
4) Sites containing tailings dams constructed using the upstream method involve the additional risk factor of more severe dam failure consequence category, but not the additional risk factors of greater height, current site storage, or capacity of the largest tailings storage facility. Excluding proposed sites and sites for which consequence categories are unclear, 63.2% of sites with upstream dams also have dams in the combined High, Very High and Extreme consequence categories, while 54.3% of sites without upstream dams have dams in the combined High, Very High and Extreme consequence categories. Excluding proposed

sites, the mean heights of the tallest dams at sites with upstream dams and sites without upstream dams are 58.4 meters and 40.3 meters, respectively, although the difference is not statistically significant.

5) The progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites shows a steady increase in the size of tailings storage facilities. The mean heights of the tallest dams at sites that are closed or under care and maintenance, operating sites, and proposed sites are 36.8 meters, 65.5 meters, and 123.9 meters, respectively. The mean current site-wide tailings storage volumes at sites that are closed or under care and maintenance, and operating sites are 22.7 and 121.5 million cubic meters, respectively. Based on the largest tailing facility on each site, the mean design tailings storage capacities at sites that are closed or under care and maintenance, operating sites, and proposed sites are 11.6 million cubic meters, 205.2 million cubic meters, and 362.3 million cubic meters, respectively
6) The progression within the BC Tailings Storage Database from sites that are either closed or under care and maintenance to operating sites to proposed sites also shows a steady increase in the severity of consequences in the event of tailings dam failure. Considering only sites with a known dam failure consequence category, for closed sites or sites under care and maintenance, 45.8% have dams in the combined High, Very High and Extreme consequence categories (implying potential loss of life), while 83.3% of operating sites have dams in the combined High, Very High, and Extreme consequence categories. Of the 11 proposed sites containing tailings storage facilities, four have dams in the consequence category Very High, one has at least one dam in the consequence category Extreme, one is in the consequence category N/A, and the rest are not yet known. The lack of any proposed sites where tailings dams are all in the failure consequence categories Low, Significant or High suggests that it is no longer economically possible to construct a tailings storage facility for which failure would result in the potential loss of fewer than 10 lives.
7) Sites with tailings storage facilities of concern were identified by comparing site locations with maps of seismic hazard zones and annual runoff. The criteria for a site of concern were location in a seismic hazard zone Very High and/or where annual runoff exceeds 2000 mm, and with one or more of the following characteristics: (a) use of upstream or unclear dam construction method (b) site status as closed or in care and maintenance (c) dam failure consequence category High, Very High, Extreme, or unclear. The 12 sites containing tailings storage facilities of concern included nine sites that are closed or in care and maintenance (Benson Lake, Bolivar/Yew Project/Texada Island Project, Eskay Creek, Johnny Mountain, New Privateer/Privateer/Zeballos, Northair, Premier Gold/Red Mountain, Quinsam North Pit, Snip), one operating site (Myra Falls), and two proposed sites (KSM, Red Mountain Underground Gold).
8) The two proposed sites KSM and Red Mountain Underground Gold have dams with failure consequence categories Extreme and Very High, respectively. The existence of proposed sites among sites with tailings storage facilities of concern cannot be overemphasized. Out of all options for stabilizing tailings dams at risk of failure or for safeguarding downstream communities, denying a permit for a facility that does not yet exist is by far the least expensive.
9) A comparison between locations of sites containing tailings storage facilities in British Columbia with salmon habitat reveals considerable threat to ecosystems. Out of the 86 sites

containing tailings storage facilities (including proposed sites), 54 are located within salmon habitat.

10) A comparison between locations of sites containing tailings storage facilities in British Columbia with municipal boundaries reveals considerable threat to communities. The many municipalities along the lower Fraser River should be regarded as particularly vulnerable to tailings dam failure at any of the 27 existing and proposed sites containing tailings storage facilities within the watershed of the Fraser River. As a single example, if the failure of the largest tailings storage facility at the HVC – Highland site released all stored tailings at the maximum capacity, nearly 1500 million cubic meters of toxic tailings would flow through the cities along the lower Fraser River. A partial list of potentially impacted cities along the lower Fraser River includes Abbotsford (population 151,683), Burnaby (population 202,799), Coquitlam (population 114,656), Delta (population 101,668), Richmond (population 182,000), Surrey (population 394,976), and Vancouver (population 600,000).
11) The risk of tailings dam failure in British Columbia has probably been underestimated since the BC Tailings Storage Database counts dams as non-upstream that are listed in mining company or government documents as constructed using the "modified centerline" method. It is particularly important to know whether any dams at the proposed sites containing tailings storage facilities have been labeled as "modified centerline."

RECOMMENDATIONS

This report makes the following recommendations to the creators of the BC Tailings Storage Database:

1) A future version of the BC Tailings Storage Database should indicate whether tailings dams have been labeled as "modified centerline" and should count these as upstream dams. It is particularly important to know whether any of the proposed tailings dams have been labeled as "modified centerline."
2) A future version of the BC Tailings Storage Database should indicate whether any portion of a tailings storage facility has been constructed on top of previously-existing tailings.
3) Sites should not be removed from the BC Tailings Storage Database until it has been convincingly demonstrated that the tailings storage facilities on the site have no remaining credible failure modes, meaning no failure modes that are physically possible, regardless of their likelihood of occurrence.

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

1) Serious consideration should be given as to the wisdom of permitting two proposed sites (KSM and Red Mountain Underground Gold) that have been identified as sites with tailings storage facilities of concern.
2) Serious consideration should be given to the designation N/A for the failure consequence category for a tailings storage facility, in terms of whether there truly are no credible failure modes (see definition above). This consideration especially applies to the proposed site Roman Coal Mine/Trend-Roman.
3) Serious consideration should be given to the fact that, out of all options for stabilizing tailings dams at risk of failure or for safeguarding downstream communities, denying a permit for a facility that does not yet exist is by far the least expensive.

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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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APPENDIX A: REVIEW OF TAILINGS DAMS

Tailings Dams and Water-Retention Dams

Although tailings dams and water-retention dams are both built for the purpose of restricting the flow of material, they are fundamentally different types of civil engineering structures. This important point was emphasized in the textbook on tailings dams by Vick (1990), "A recurring theme throughout the book is that there are significant differences between tailings embankment and water-retention dams … Unlike dams constructed by government agencies for water-retention purposes, tailings dams are subject to rigid economic constraints defined in the context of the mining project as a whole. While water-retention dams produce economic benefits that presumably outweigh their cost, tailings dams are economic liabilities to the mining operation from start to finish. As a result, it is not often economically feasible to go to the lengths sometimes taken to obtain fill for conventional water dams." In addition to the economic unfeasibility of traveling the distances that are sometimes ideal for obtaining appropriate fill, Vick (1990) gives many other examples of ways in which it is not economically feasible to build a tailings dam in the same way as a water-retention dam. An earthen water-retention dam is constructed out of rock and soil that is chosen for its suitability for the construction of dams. However, a tailings dam is normally built out of construction material that is created by the mining operation, such as the waste rock that is removed before reaching the ore, or the mine tailings themselves after proper compaction. In addition, a water-retention dam is built completely from the beginning before its reservoir is filled with water, while a tailings dam is built in stages as more tailings are produced that require storage and as material from the mining operation (such as waste rock) becomes available for construction.

The consequences of the very different constructions of tailings dams and water-retention dams are the very different safety records of the two types of structures. According to a widely-cited paper by Davies (2002), "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 to 1 in 1750. This rate of failure does not offer a favorable comparison with the less than 1 in 10,000 that appears representative for conventional dams. The comparison is even more unfavorable if less 'spectacular' tailings dam failures are considered. Furthermore, these failure statistics are for physical failures alone. Tailings impoundments can have environmental 'failure' while maintaining sufficient structural integrity (e.g. impacts to surface and ground waters)." Both the total number of tailings dams and the number of tailings dams failures cited by Davies (2002) are probably too low. However, the Independent Expert Engineering Investigation and Review Panel (2015b) found a similar failure rate in tailings dams of 1 in 600 per year during the 1969-2015 period in British Columbia. The completeness of the above databases is discussed further in the subsection Emerging Tailings Dam Databases.

The preceding discussion largely contrasts tailings dams and water-retention dams that are in active operation. 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. On the other hand, a tailings dam cannot be dismantled unless the tailings can be moved to another location, such as an abandoned open pit. Typically, a tailings dam is expected to confine the toxic tailings in perpetuity, although normally the monitoring, inspection and maintenance of the dam cease at some point after the end of the mining project. 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."

Methods of Construction of Tailings Dams

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. A1). 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.

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, rock fill, mine waste rock or the tailings from an earlier episode of ore processing (see Figs. A2a-c). In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. As mentioned earlier, it is most common to build successive dikes from waste rock or the coarser fraction of tailings (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. A2a). The downstream construction method is the most expensive since it requires the most construction material (compare Figs. A2a and A2b). 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. A2a-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. A2c).

The advantages and disadvantages of different types of construction in terms of their ability to resist catastrophic failures will be discussed after reviewing the common causes of failure of tailings dams.

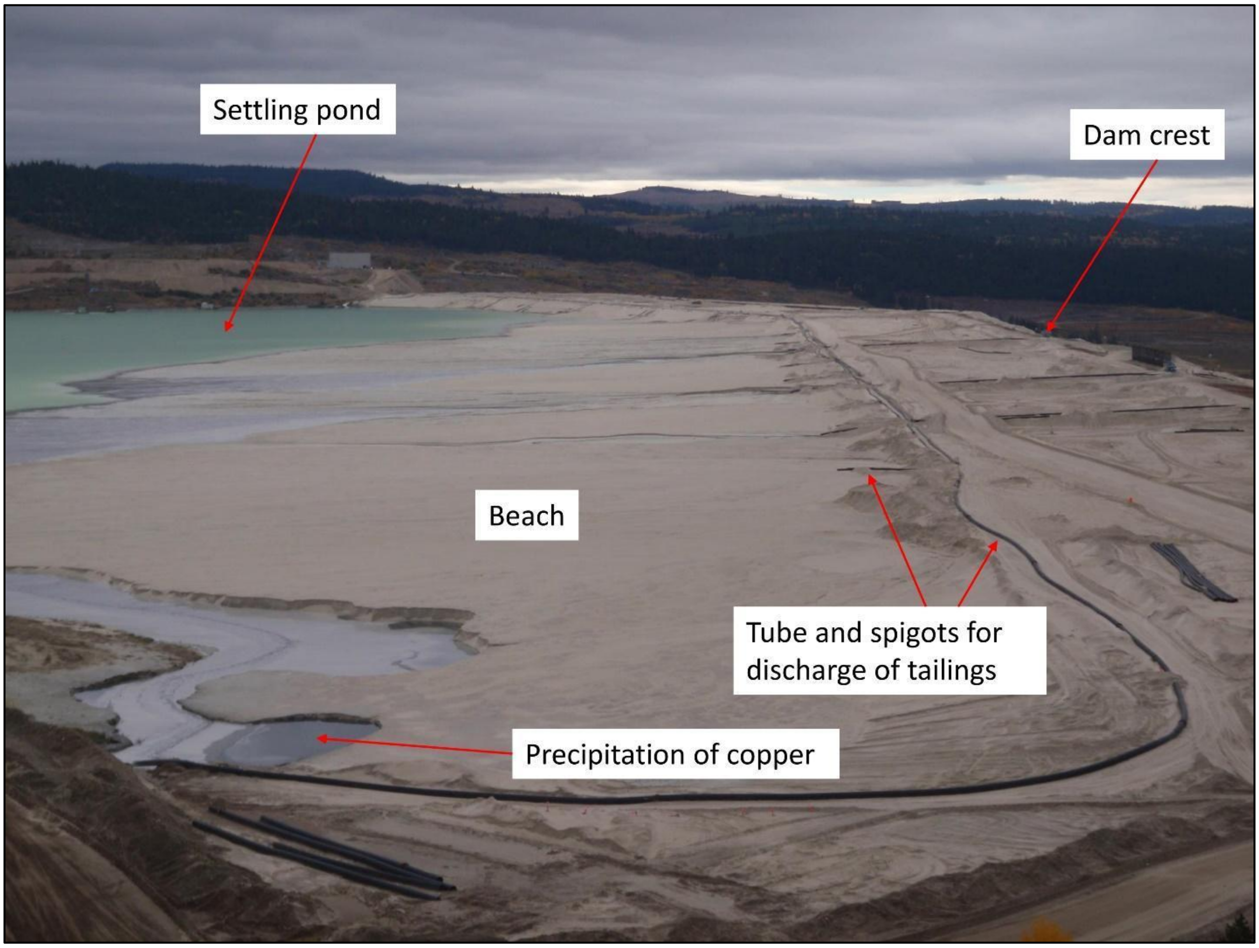

Figure A1. In conventional tailings management, tailings and water from the ore processing plant are injected in the upstream direction from spigots along the dam crest. The coarser tailings settle closer to the dam crest to form a beach. The finer tailings and water travel farther upstream where the 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.

Causes of Failure of Tailings Dams

The most common causes of failures of tailings dams are seismic liquefaction, static liquefaction, overtopping by floods, internal erosion, and foundation failure. The phenomenon of liquefaction is best explained by beginning with first principles of soil mechanics. From an engineering perspective, a mass of mine tailings, consisting of solid rock particles in which the pores between the particles are filled with a combination of air and water, is a type of soil. The phrases “soil” and “mass of tailings” will be used interchangeably in this review of liquefaction, which largely follows the presentation in Holtz et al. (2011).

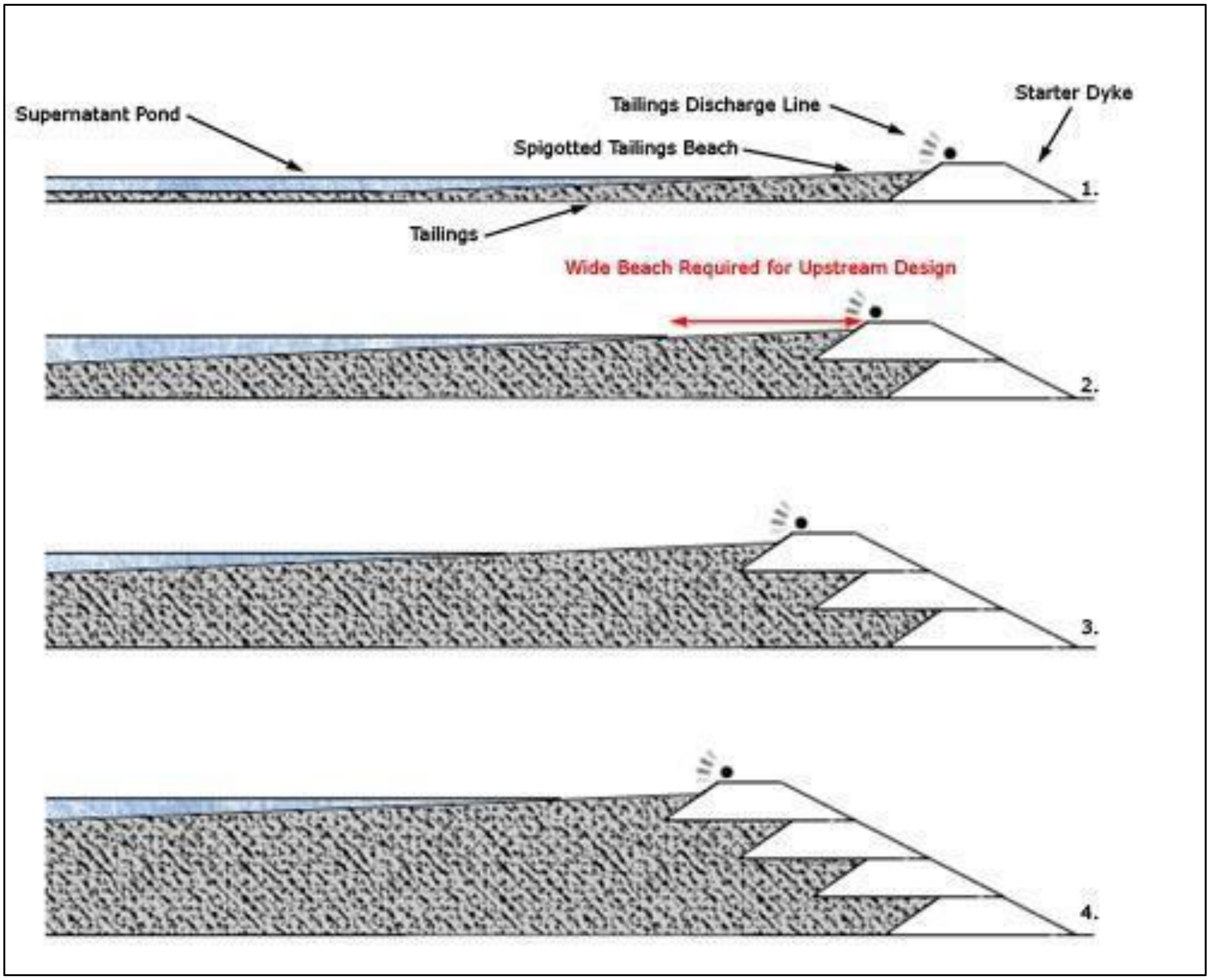

Figure A2a. In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. Dikes can be constructed with mine waste rock, natural soil, natural rock fill, or the coarser fraction of tailings (with proper compaction). The advantage 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. Dams constructed by this method are also susceptible to failure by overtopping or internal erosion when the beach is too narrow due to an insufficient amount of sand in the discharged tailings or excessive water in the settling pond. Figure from TailPro Consulting (2022).

A normal stress means any stress that is acting perpendicular to a surface (see Fig. A3). 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. A3). 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 without compaction. 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 other. Sufficient water pressure can offset the normal stress, so that little consolidation could occur and at a slow rate.

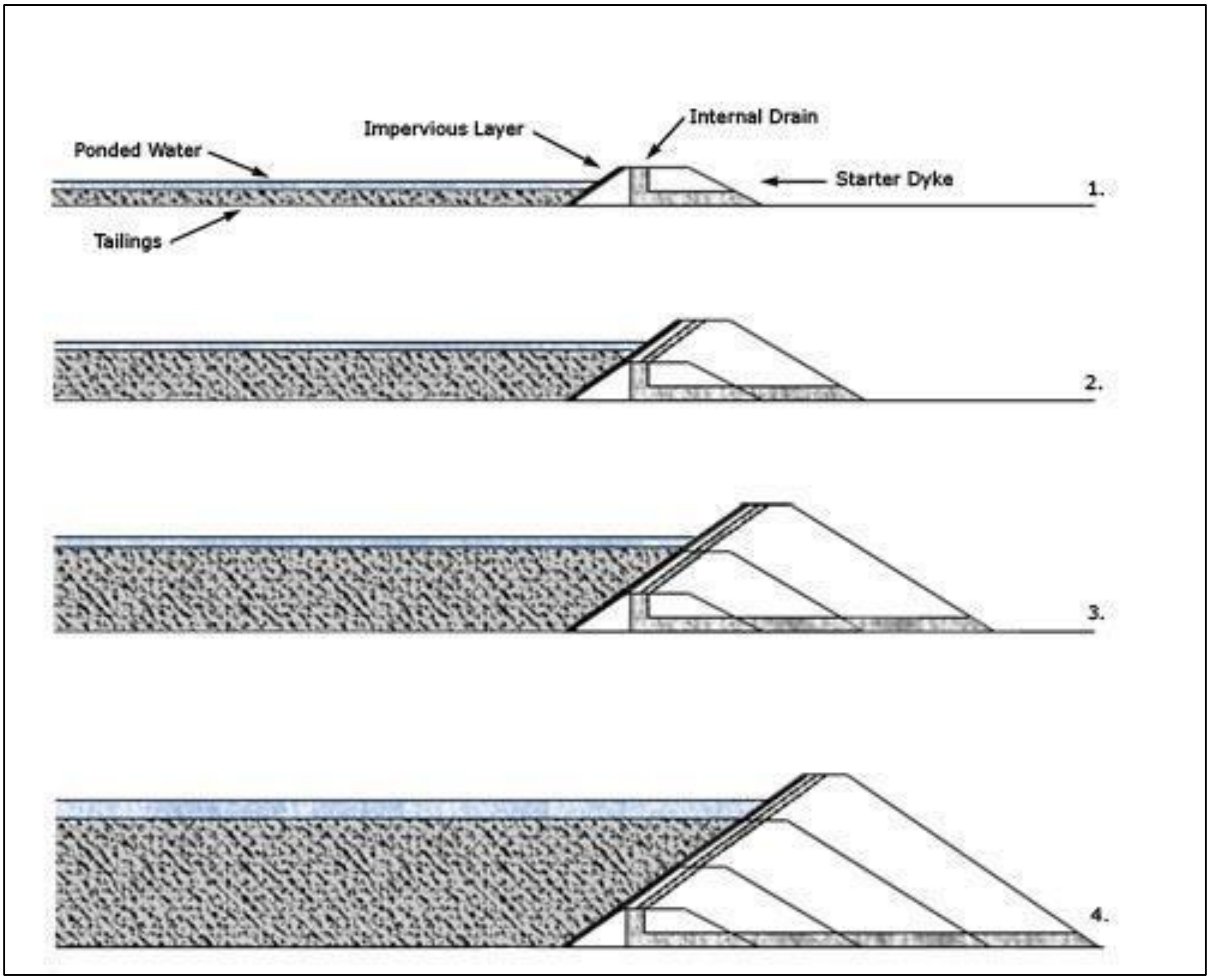

Figure A2b. In the downstream construction method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. Dikes can be constructed from mine waste rock, natural soil, natural rock fill, or the coarser fraction of tailings (with proper compaction). The 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. A2a and A2b). Figure from TailPro Consulting (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. A3). In the diagram on the left-hand side of Fig. A4, 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. A4), 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.

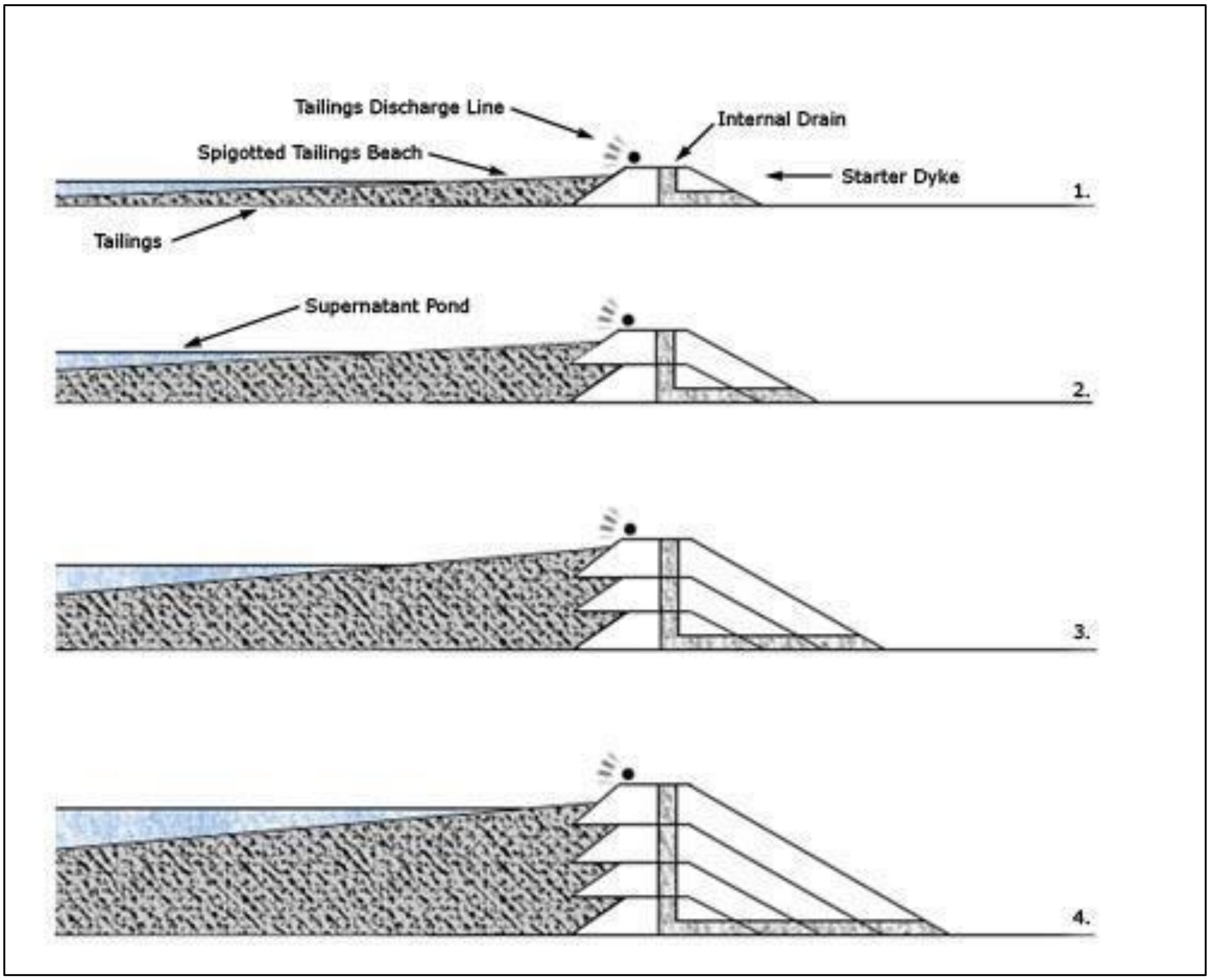

Figure A2c. In the centerline construction method, successive dikes are constructed by placing construction material on the beach and on the slope downstream of the previous dike. The central lines of the rises coincide as the dam is built upwards. Dikes can be constructed from mine waste rock, natural soil, natural rock fill, or the coarser fraction of tailings (with proper compaction). The centerline method is intermediate between the upstream and downstream methods (see Figs. A2a-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).

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 a disturbance or a trigger. Seismic liquefaction results from the cyclic stresses that occur during earthquakes or the vibrations from drilling, blasting or excessive vehicular traffic. Static liquefaction results from non-cyclic stresses, such as an increase in the load of tailings (especially when tailings are added so fast that the underlying tailings do not have time to consolidate) or heavy rainfall. 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. A4). 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. A3). 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.

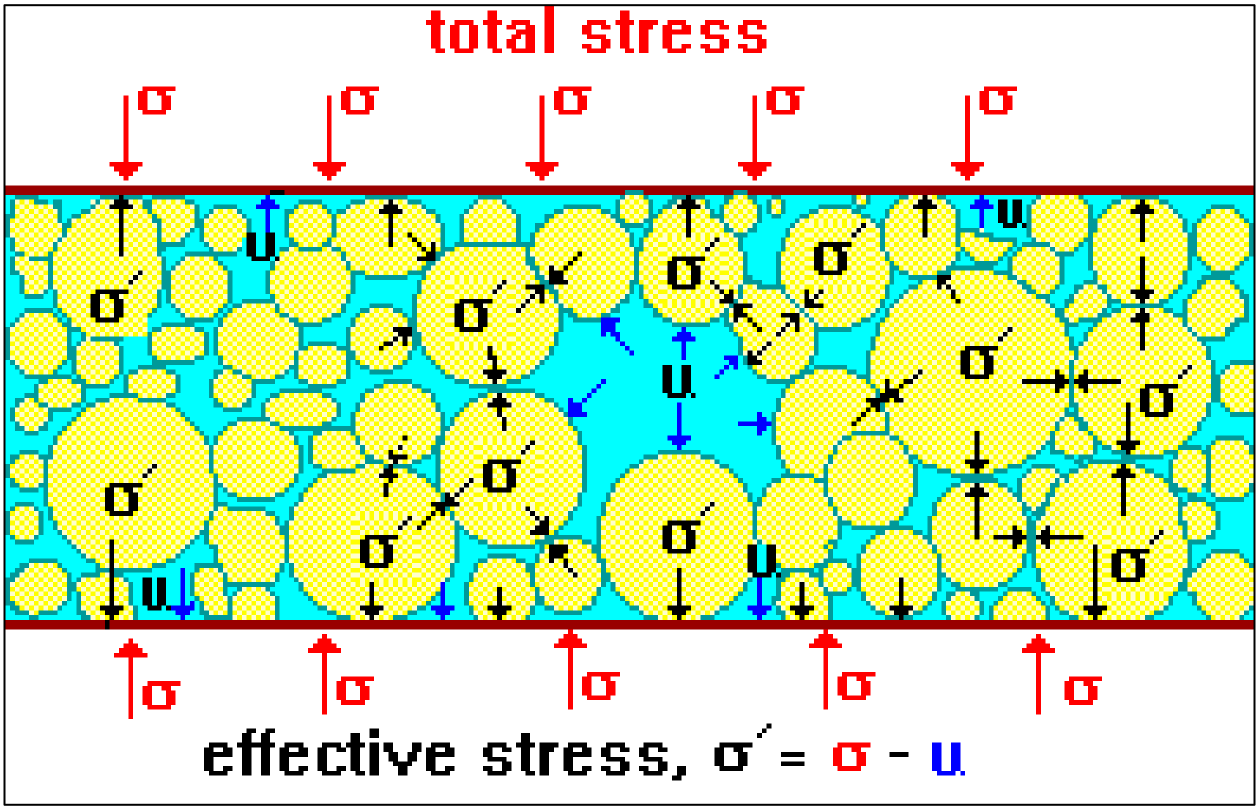

Figure A3. The effective stress in soil is equal to the total stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other. Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress. Figure from GeotechniCAL (2022).

This phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles. Conventional tailings storage facilities are especially susceptible to liquefaction because of their deposition by hydraulic discharge without subsequent compaction (see Fig. A1). Even if the pores between loosely-packed particles are unsaturated prior to the disturbance, some compaction can occur during disturbance (thus 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, a mix of fine and coarse particles could make the tailings more susceptible to liquefaction by reducing their permeability (the fine particles will fill in the pores between the coarse particles). Further information on soil and tailings mechanics will be provided in the subsection Cause of Failure of the Tailings Dam at Brumadinho.

Seismic liquefaction of earthen water-retention dams can occur, but static liquefaction of such dams is now quite rare, since, unlike tailings dams, earthen water-retention dams are no longer constructed by hydraulic discharge without compaction (compare with Fig. A1). The other causes of dam failure (overtopping, internal erosion, and foundation failure) apply to both tailings dams and earthen water-retention dams. Any flow of water over an earthen dam tends to erode away the outer embankment, resulting in either a breach of the embankment or its total disappearance. Internal erosion occurs when the seepage through an earthen dam washes away the solid particles of the dam, so that the dam loses its structural integrity. The appearance of mud in the seepage through a dam face is generally regarded as the beginning of internal erosion. Internal erosion is caused by an excessive hydraulic gradient that forces water to flow through the dam fast enough that it can transport solid particles. Internal erosion in tailings dams is prevented by reducing the water content of the tailings (and thus the volume of water stored behind the dam), lengthening the hydraulic flow paths (for example, by decreasing the slopes of embankments) and by forcing water to exit at the base of dams rather than along the face (for example, by installing appropriate drains). The installation of filters is usually regarded as essential in order to trap any solid particles that would be dislodged by the flow of water through the dam. Failure of the foundation (the earth beneath the tailings storage facility or beneath the dam itself) can be a type of static liquefaction. Foundation failure can occur when excessive loading or excessive water in the mass of tailings forces the water into a foundation that has insufficient permeability for the water to pass through the foundation or when the foundation was insufficiently compacted prior to construction of the tailings storage facility.

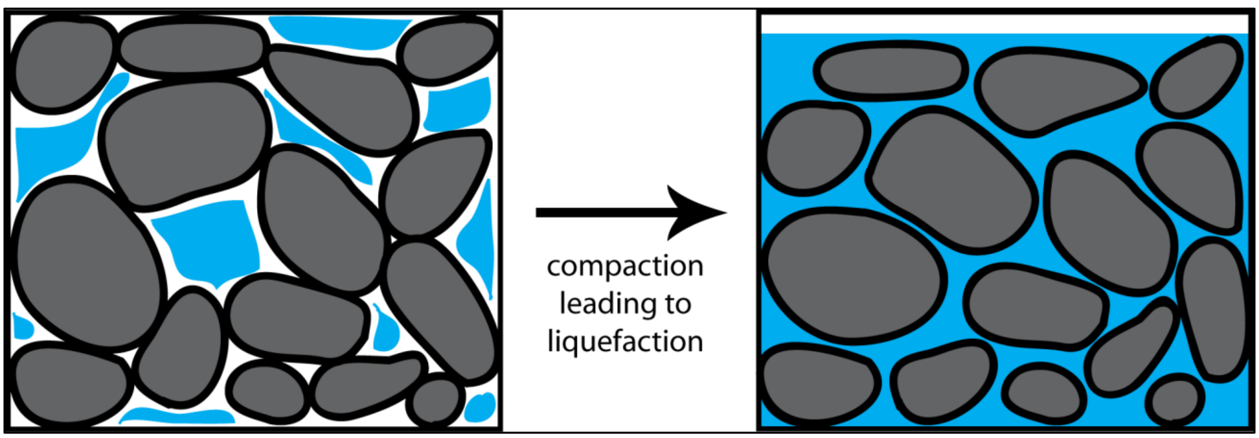

Figure A4. In the diagram on the left, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other, so that the load is supported by the particles (and partially by the water). Loose-packing means that the soil is in a contractive state, so that 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. A3). 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).

Construction Methods and Causes of Failure

The common methods of tailings dam construction can now 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. A2a). 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. A2c). 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. A2b). 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. A2a; 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.

Based on the review of the common causes of failure, it should be clear that, besides avoiding the upstream construction method, the key to reducing the probability of tailings dam failure by any common failure mode (seismic or static liquefaction, overtopping by floods, internal erosion, foundation failure) is lowering the water table within both the tailings deposit and the tailings dam, and reducing the water content of the tailings. Lowering the water table and reducing the water content of the tailings and the tailings dam can also reduce the consequences of failure because unsaturated tailings will be more likely to slump, rather than develop into a liquefied flow. The problem with the upstream construction method is that there are fewer options for lowering the water table both within the tailings dam and the tailings deposit. In the downstream and centerline construction methods, the water table can be lowered within the tailings dam by installing low-permeability layers or cores on the upstream side of the dam (compare Figs. A2b-c with Fig. A5). However, in the upstream construction method, there is no place to put such a low-permeability layer or core (compare Fig. A2a with Fig. A5). Both the downstream and centerline construction methods allow the installation of chimney drains and blanket drains (compare Figs. A2b-c and A6), which are other ways of lowering the water table both within the tailings deposit and the tailings dam. The upstream construction method does not have any place to install a chimney drain (see Fig. A2a), although blanket drains are possible (see Fig. A6).

In fact, in the upstream construction method, the maintenance of a low water table within the tailings dam and the tailings deposit close to the dam is highly dependent on the maintenance of a sufficiently wide beach for keeping the settling pond far from the dam crest (see Fig. A1). The beach can be overtaken by the pond if there is heavy rainfall in the watershed of the tailings storage facility or even if there is not enough sand in the tailings to form a suitable beach. For example, the tailings pond at the Highland Valley Copper mine has a very narrow beach, which hardly exists on the far side of the tailings pond (see Fig. A1). This narrow beach is probably the result of insufficient coarse particles in the tailings stream from the ore processing plant. (The tailings dam at the Highland Valley Copper mine was actually built by the centerline method. Although a suitable beach is still important, tailings dams built by the centerline method have other means for maintaining a low water table, as explained above.)

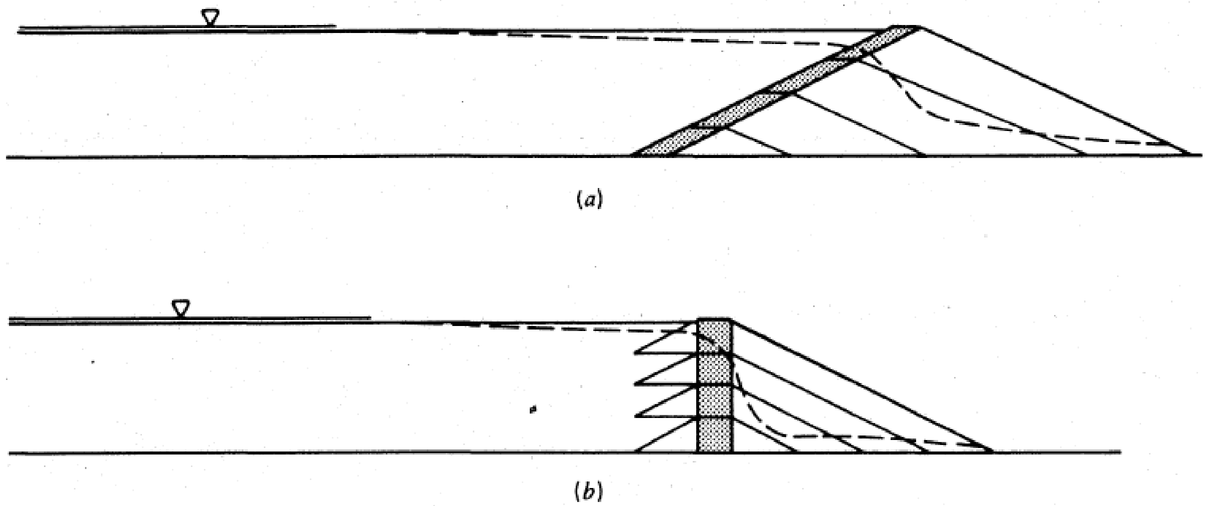

Figure 7.2 Use of low-permeability cores in raised embankments. (*a*) Downstream embankment. Phreatic surface indicated by dashed line. (*b*) Centerline embankment.

Figure A5. One of the advantages of the downstream and centerline construction methods is that it is possible to install low-permeability cores to lower the water table at the toe of the dam. This decrease in the water table reduces the likelihood of internal erosion of the dam, seismic or static liquefaction of the tailings dam or tailings deposit, and failure of the foundation under the tailings. These low-permeability cores are almost impossible to install when using the upstream construction method (see Fig. A2a). Figure from Vick (1990).

Based upon the preceding engineering principles and the available historical record, 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).

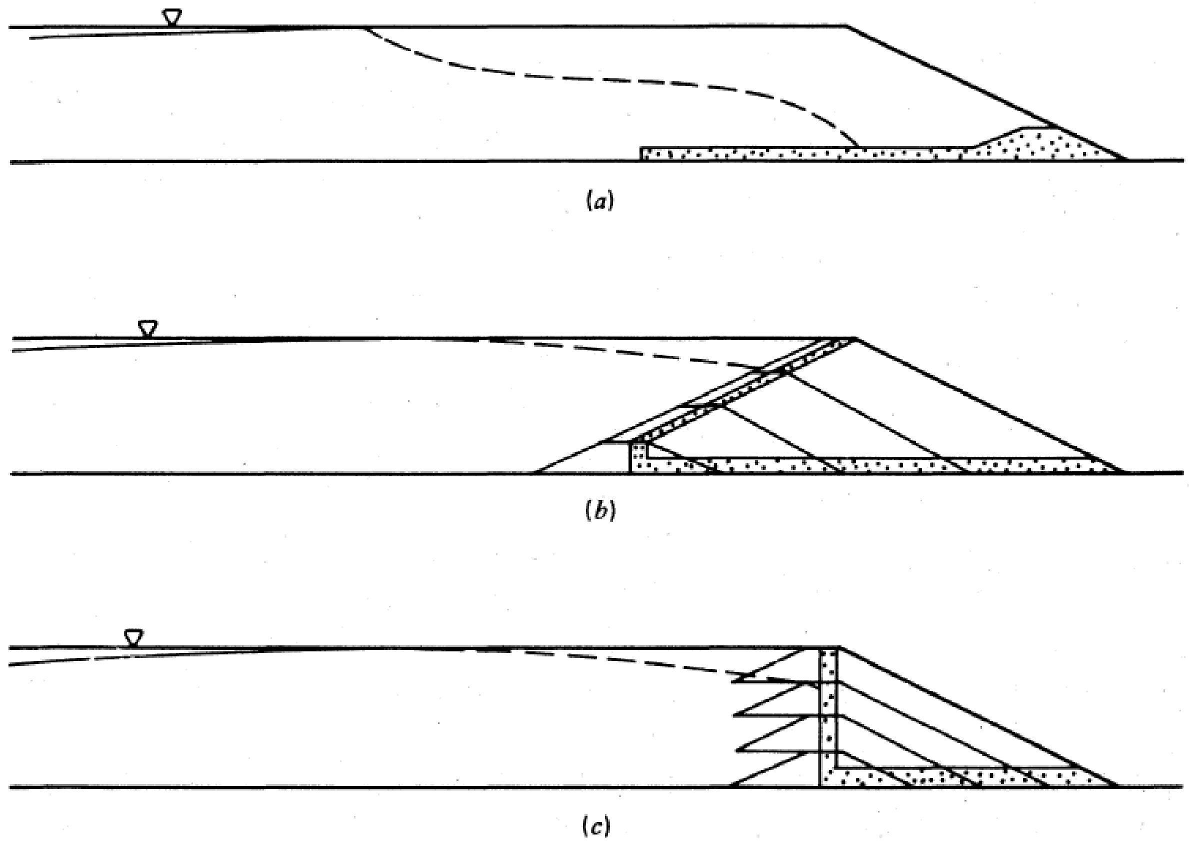

Figure 7.3 Use of internal drainage zones in raised embankments. (*a*) Upstream embankment using pervious starter dike with upstream blanket drain. (*b*) Downstream embankment using inclined chimney drain and blanket drain. (*c*) Centerline embankment with vertical chimney drain and blanket drain.

Figure A6. It is possible to install blanket drains using all three construction methods, although chimney drains can be installed using only the downstream and centerline construction methods. These drains lower the water table and reduce the likelihood of internal erosion of the tailings dam, seismic or static liquefaction of the tailings dam or tailings deposit, and failure of the foundation under the tailings. Figure from Vick (1990).

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 (see Table A1; 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 (see Table A1). 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 (SNGM, 2020).

Table A1. Construction methods of tailings dams that failed during Chilean earthquakes[1]

Dam	City, Region	Construction Method
March 28, 1965, Magnitude = 7.4		
El Cerrado	Cabildo, Valparaíso	Upstream
El Cobre Viejo	Nogales, Valparaíso	Upstream
El Cobre Chico	Nogales, Valparaíso	Upstream
El Cobre Nuevo	Nogales, Valparaíso	Downstream
Cerro Negro No. 1	Cabildo, Valparaíso	Upstream
Cerro Negro No. 2	Cabildo, Valparaíso	Upstream
Cerro Negro No. 3	Cabildo, Valparaíso	Upstream
Hierro Viejo	Petorca, Valparaíso	Upstream
Los Maquis 1	Cabildo, Valparaíso	Upstream
Los Maquis 3	Cabildo, Valparaíso	Upstream
La Patagua	La Ligua, Valparaíso	Upstream
Bellavista	San Felipe, Valparaíso	Upstream
El Sauce 1	Llay Lay, Valparaíso	Upstream
El Sauce 2	Llay Lay, Valparaíso	Upstream
El Sauce 3	Llay Lay, Valparaíso	Upstream
El Sauce 4	Llay Lay, Valparaíso	Upstream
Ramayana	Valparaíso	Upstream
November 7, 1981, Magnitude = 6.5		
Veta del Agua No. 2	Nogales, Valparaíso	Upstream
March 3, 1985, Magnitude = 7.8		
Veta del Agua No. 1	Nogales, Valparaíso	Upstream/Centerline
Cerro Negro No. 4	Cabildo, Valparaíso	Upstream/Centerline
Cobre No. 4	Nogales, Valparaíso	Downstream
October 14, 1997, Magnitude = 7.0		
Almendro	Vallenar	Upstream
Algarrobo	Vallenar	Upstream
Maitén	Vallenar	Upstream
Tranque Antiguo Planta La Cocinera	Vallenar, Vallenar	Upstream/Centerline
February 27, 2010, Magnitude = 8.8		
Tranque Adosado Planta Alhué	Alhué, Region Metropolitana	Downstream
Las Palmas	Pencahue, Maule	Unknown
Tranque Planta Chacón	Cachapoal, Rancagua	Unknown
Veta del Agua Tranque No. 5	Nogales, Valparaíso	Upstream
Tranque No. 1 (Minera Clarita)	San Felipe, Valparaíso	Upstream

[1]Data from Villavicencio et al. (2013)

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."

Martin et al. (2002) took a different approach in writing "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.)

Some of the ten rules by Martin et al. (2002) are illustrated in Fig. A7, which is intended to show an off-the-shelf design that fulfills four out of the ten rules. By allowing the design water table (phreatic level) to rise to within one-half of the height of the dam (see Fig. A7), the designers violated the rule that "a sufficiently wide beach-above-water (BAW), relative to the ultimate height of the dam, must be maintained at all times … the dam slope must not be underlain by tailings slimes (beach-below-water - BBW) …" (Martin et al., 2002). Moreover, the embankment slope of 3H:1V (see Fig. A7) violated the rule that "upstream dams should be raised at slopes of 4H:1V or flatter" (Martin et al., 2002). On the other hand, the filters and under-drainage for the starter dike probably satisfy the rule stating, "There must be sufficient underdrainage (drainage blanket, finger drains) and/or a pervious foundation to maintain the sand shell in a relatively drained condition, and to prevent seepage gradients from issuing from the face of the tailings dam." The critique of Martin et al. (2002) by Morrill et al. (2020) will be provided in the section Post-Brumadinho Guidance and Data on Upstream Dams.

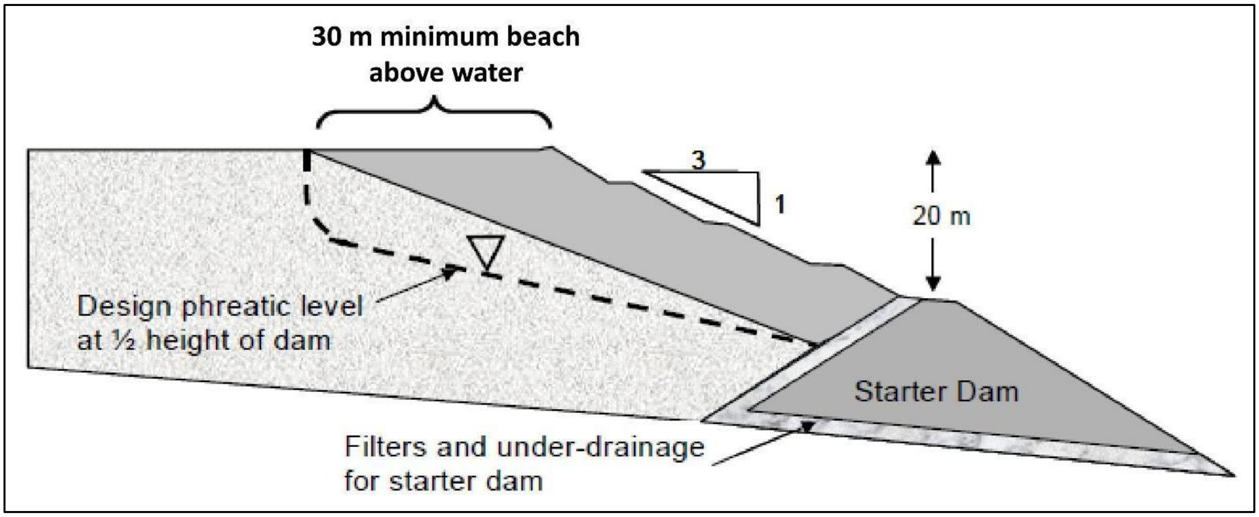

Figure A7. Martin et al. (2002) listed ten rules for the safe construction of upstream dams with the warning that "of the 10 rules, a 'score' of 9/10 will not necessarily have a better outcome than 2/10, as any omission creates immediate candidacy for an upstream tailings dam to join the list of facilities that have failed due to ignoring some or all of the rules." It should be noted that, at the present time, "there is a broad consensus within the engineering community 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" (Morrill et al., 2020). Some of the ten rules by Martin et al. (2002) are illustrated in the above figure, which is intended to show an off-the-shelf design that fulfills four out of the ten rules. By allowing the design water table (phreatic level) to rise to within one-half of the height of the dam, the designers violated the rule that "a sufficiently wide beach-above-water (BAW), relative to the ultimate height of the dam, must be maintained at all times … the dam slope must not be underlain by tailings slimes (beach-below-water - BBW) …" (Martin et al., 2002). Moreover, the embankment slope of 3H:1V violated the rule that "upstream dams should be raised at slopes of 4H:1V or flatter" (Martin et al., 2002). On the other hand, the filters and under-drainage for the starter dike probably satisfy the rule stating, "There must be sufficient underdrainage (drainage blanket, finger drains) and/or a pervious foundation to maintain the sand shell in a relatively drained condition, and to prevent seepage gradients from issuing from the face of the tailings dam." The concept of the "sand shell" is explained further in Fig. A8. Figure from Martin et al. (2002).

Although ICOLD Bulletin 181 Tailings Dam Design—Technology Update (ICOLD, 2021) was written after the Brumadinho disaster, one aspect of the bulletin is necessary for understanding the geotechnical significance of the zone consisting of the dikes plus the succession of beaches (the gray polygon shown in Fig. A7). According to ICOLD (2021), "The outer zone, referred to as the structural zone (shown with a red dashed line), becomes the retaining structure" (see Fig. A8). In other words, in the upstream construction method, the succession of beaches (and essentially all other tailings that directly underlie the dikes) is intended to form part of the structural zone along with the dikes (compare Figs. A2a, A7 and

A8). However, the stack of beaches can perform as a structural zone only if the beaches can be compacted by the overlying weight of dikes and other beaches and if the beaches remain unsaturated (above the water table). As a caution, ICOLD (2021) adds, “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.” Additional cautions from ICOLD (2021) and the significance of the structural zone will be further discussed in the subsection Post-Brumadinho Guidance on Brittle Tailings: Implications for Upstream Dams

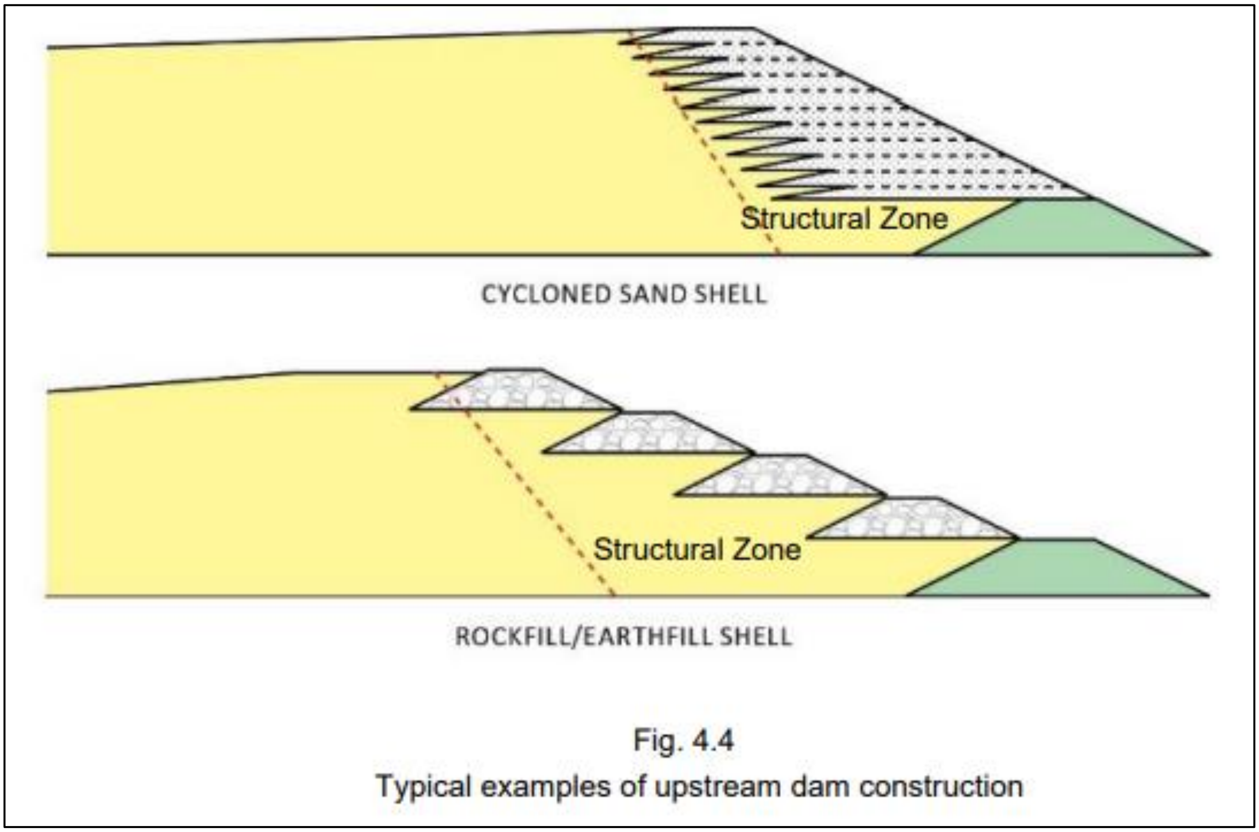

Figure A8. According to ICOLD (2021), “The outer zone, referred to as the structural zone (shown with a red dashed line), becomes the retaining structure.” In other words, in the upstream construction method, the beach is intended to form part of the structural zone along with the dikes (compare with Figs. A2a and A7). The stack of beaches can perform as a structural zone only if the beaches can be adequately compacted by the overlying weight of dikes and beaches and if the beaches remain unsaturated (above the water table). As a caution, ICOLD (2021) adds, “ICOLD Bulletin B 121 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.” Since the upcoming ICOLD bulletin on tailings dam safety states that “Brittle materials should never be allowed in the structural zones of new facilities” (Ridlen, 2021), the use of the upstream construction method with brittle tailings is extremely problematic, if not impossible. Figure from ICOLD (2021).

Cause of Failure of the Tailings Dam at Brumadinho

On January 25, 2019, a dam impounding iron-ore tailings failed near Brumadinho, Brazil, resulting in nearly 300 deaths, the vast majority of whom were mineworkers (Robertson et al., 2019). Although the name of the tailings dam was Dam 1 and the name of the mine is Córrego do Feijão, the tailings dam is now typically referred to as the Brumadinho dam, and that name will be used in this report. In the aftermath of the Brumadinho disaster, a great deal of new data and regulations on tailings dams have emerged, as well as new industry guidance documents. Some key industry guidance documents on tailings dams are still in final draft form and are scheduled for official release in 2022.

The tailings dam at Brumadinho was constructed using the upstream method and was 86 meters high at the time of failure. The dam had been constructed over a 37-year period from 1976 to 2013 in 15 stages, corresponding to 10 raises. There were no new raises after 2013 and the deposition of new tailings behind the dam had ceased in 2016. The dam was storing 12 million cubic meters of tailings, of which 9.7 million cubic meters were released during the dam failure (Robertson et al., 2019).

The expert review panel report on the failure of the tailings dam at Brumadinho concluded that the failure occurred due to static liquefaction and drew attention to the importance of brittle tailings in the process of liquefaction (Robertson et al., 2019). Brittle materials exhibit very little strain (deformation) in response to an applied stress. Conversely, brittle materials develop a very large stress in response to a small strain. As the strain is increased, the stress increases until it reaches a maximum stress called the peak strength or yield strength. Any additional strain will then cause the strength to suddenly drop to a value called the residual strength. The upcoming report by Klohn Crippen Berger (2022) is another excellent review of the Brumadinho failure and the significance of brittle tailings for the stability of tailings storage facilities.

Table 2: XRD Results – June 2019 Samples

Mineral	Ideal Formula	# 1 Sample 1 Bag 2 X-ray (Slimes)	# 2 Sample 1 Bag 4 X-ray (Slimes)	# 3 Sample 3 Bag 2 X-ray (Coarse Tailings)	# 4 Sample 5 Bag 1 X-ray (Coarse Tailings)
Hematite	α-Fe_2O_3	50.1	44.4	87.7	86.8
Goethite	A-$Fe^{3+}O(OH)$	32.0	34.0	3.4	3.0
Magnetite	Fe_3O_4	0.4	0.4	6.5	7.6
Quartz	SiO_2	5.4	6.6	1.6	1.5
Kaolinite	$Al_2Si_2O_5(OH)_4$	6.2	8.9	0.6	0.6
Talc	$Mg_3Si_4O_{10}(OH)_2$	2.7	2.3	-	-
Gibbsite	$Al(OH)_3$	0.9	1.0	0.3	0.4
Bayerite	$Al(OH)_3$	2.2	2.4	-	-
Total		100.0	100.0	100.0	100.0

Figure A9a. The iron-ore tailings at the Brumadinho tailings storage facility were 77% iron oxides (hematite, goethite, magnetite) with a range of 62-98% (see additional data in Fig. A9b). Table from Robertson et al. (2019).

Table 3: XRD Results – July 2019

Mineral	Ideal Formula	DT-01 (Slimes)	DT-02 (Slimes)	DT-06 (Fine Tailings)	DT10 (Fine Tailings)
Hematite	α-Fe_2O_3	43.1	54.1	50.3	44.3
Goethite	A-$Fe^{3+}O(OH)$	20.7	15.3	10.2	13.7
Magnetite	Fe_3O_4	1.9	1.5	1.3	1.3
Quartz	SiO_2	14.9	12	28.5	21.8
Kaolinite	$Al_2Si_2O_5(OH)_4$	11.6	10.9	6.4	13.5
Talc	$Mg_3Si_4O_{10}(OH)_2$	3.1	2	1.4	1.1
Gibbsite	$Al(OH)_3$	3	2.2	1.4	3
Bayerite	$Al(OH)_3$	1.7	2	0.5	1.4
Total		100.0	100.0	100.0	100.0

Figure A9b. The iron-ore tailings at the Brumadinho tailings storage facility were 77% iron oxides (hematite, goethite, magnetite) with a range of 62-98% (see additional data in Fig. A9a). Table from Robertson et al. (2019).

Brittle behavior can initiate liquefaction because the sudden strength loss of tailings or other solid particles can initiate a sudden tendency of loosely-packed particles to contract or consolidate (see Fig. A4). As discussed earlier, if the pores are saturated and the pore water cannot escape (due to low permeability or the speed of the deformation), the pore water will be pressurized, thus, breaking the contact between the particles (see Fig. A4). In this way, static liquefaction itself can be understood as a type of brittle behavior, in which saturated tailings undergo a sudden and substantial loss of strength once a peak or yield strength has been exceeded. Thus, the residual strength is also known as the liquefied strength or the post-liquefaction strength. Unlike the idealized diagram in Fig. A4, the liquefied strength is small but not literally zero (except in highly-controlled laboratory conditions) because any movement of the mass of tailings and water will re-establish some contact between the particles.

Robertson et al. (2019) used X-ray diffraction to find, perhaps unsurprisingly, that the iron-ore tailings at the Brumadinho dam had a very high content of iron oxides (hematite, goethite, magnetite) with a mean content of 77% by mass and a range of 62-98% (see Figs. A9a-b). Scanning electron microscope images showed the formation of iron oxide bonds between the coarse tailings (see Figs. A10a-b). According to Robertson et al. (2019), these iron oxide bonds resulted from the gradual dissolution and then re-precipitation of the iron oxide minerals. The iron oxide bonding was equivalent to a weak cementation of the tailings. The iron oxide bonds were stiff (or brittle) so that little deformation resulted from applied stress.

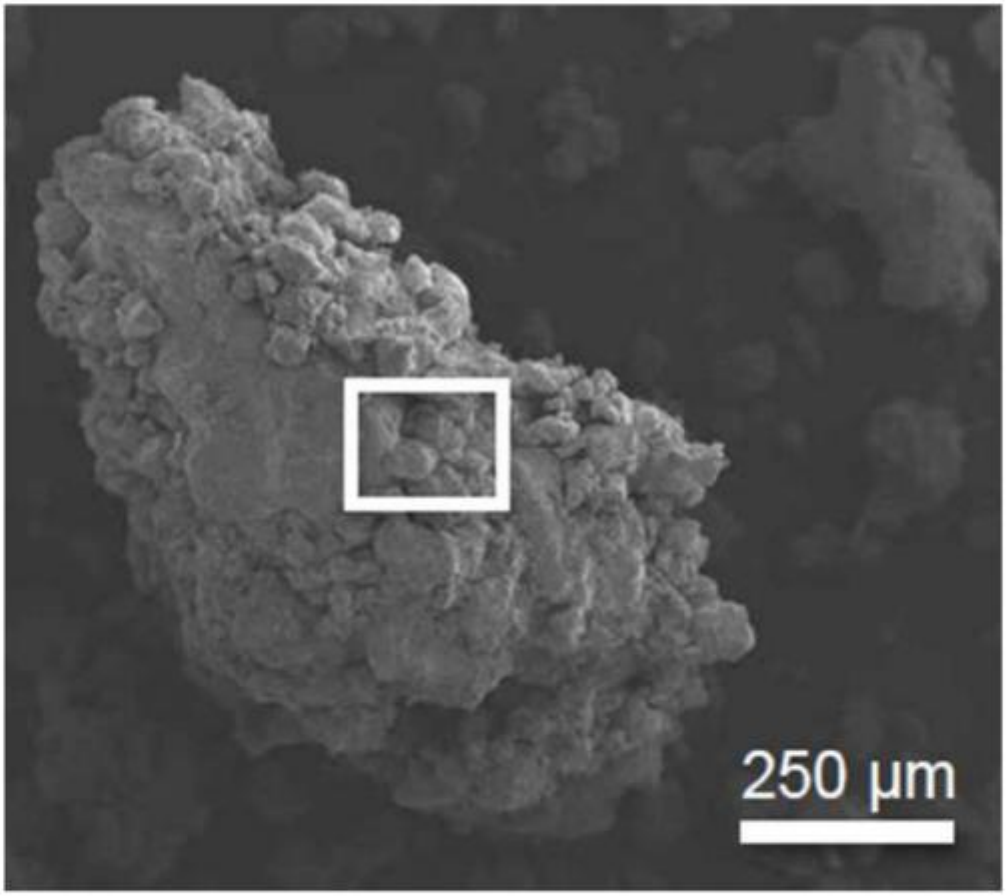

Figure 33: SEM Image of Coarse Tailings

Figure A10a. The high iron oxide content of the iron-ore tailings at the Brumadinho tailings storage facility promoted the dissolution and re-precipitation of iron oxides and, thus, the formation of iron oxide bonds between the tailings. See close-up of iron oxide bonding in Fig. A10b. Figure from Robertson et al. (2019).

The static liquefaction was initiated by a combination of two events. The gradual consolidation of the tailings (on the order of millimeters) caused a gradual increase in the stress on the iron oxide bonds between the tailings (see Fig. A11). In other words, a small “stretching” of the stiff or brittle bonds gradually increased the stress on the bonds almost to their peak or yield strength. The heavy rainfall in the months preceding the failure caused pores that were previously unsaturated to become saturated. The saturation of the pores resulted in a loss of strength so that the existing stress from the slow downward creep (see Fig. A11) caused the iron oxide bonds to break, which triggered the static liquefaction (Robertson et al., 2019). Following the liquefaction, the upstream tailings dam collapsed backward and downward into the liquefied tailings. According to Robertson et al. (2019), “The dam crest dropped and the area above the toe region bulged outwards before the surface of the dam broke apart … The videos show that the initial failure was relatively shallow and was followed by a series of rapid shallow slips with steep back slopes that progressed backwards into the tailings impoundment.” Robertson et al. (2019) stressed that the liquefaction occurred with no warning or precursors, which is typical of brittle phenomena.

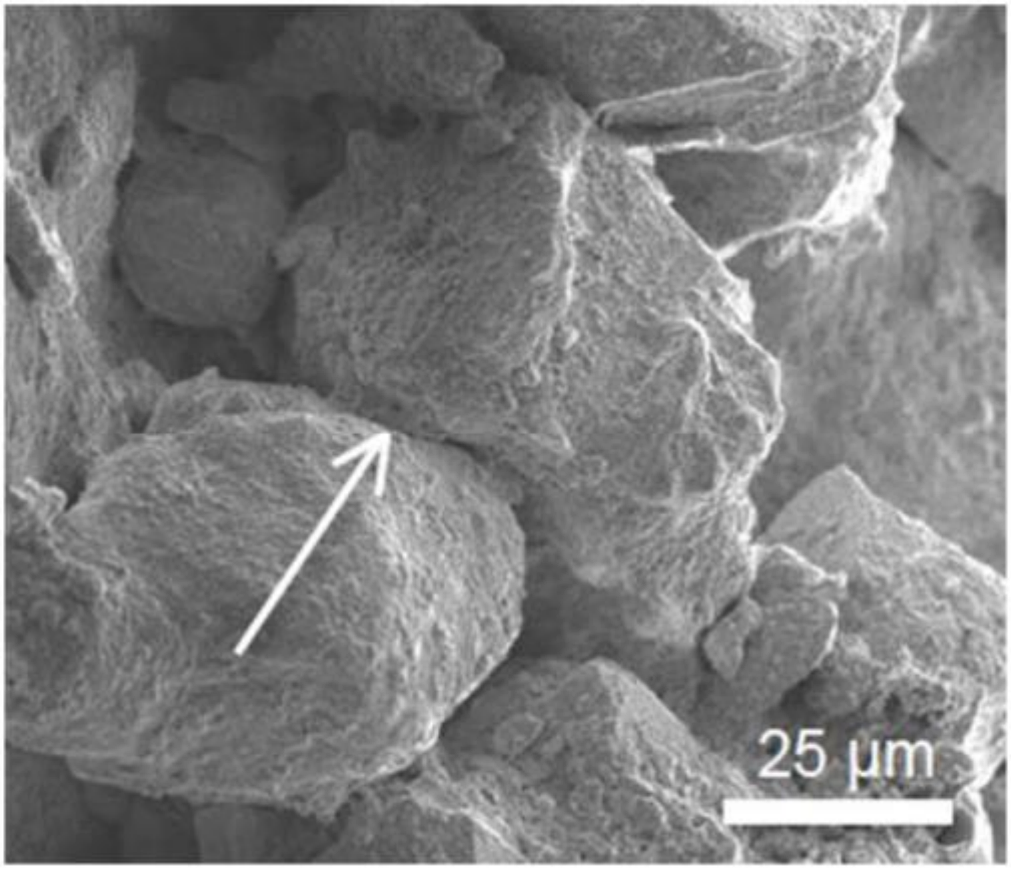

Figure 34: SEM Image of Coarse Tailings (Detail of Box Shown in Figure 33). Region Highlighted with Arrow Shows Bonding Between Particles

Figure A10b. The high iron oxide content of the iron-ore tailings at the Brumadinho tailings storage facility promoted the dissolution and re-precipitation of iron oxides and, thus, the formation of iron oxide bonds between the tailings. See larger-scale view in Fig. A10a. Figure from Robertson et al. (2019).

Robertson et al. (2019) emphasized the importance of the iron oxide bonding for the brittle nature of the iron-ore tailings (see Fig. A12). Not all materials have a peak strength with a strength loss after the peak strength has been exceeded. Some materials will show an indefinite increase in strength as the strain is increased. These materials are known as strain-hardening (see Fig. A12). Materials that show a decrease in strength as the strain is increased (usually above some critical strain or stress) are called strain-softening (see Fig. A12). Butter is a good example of a household material with strain-softening behavior. The butter has enough strength to remain as a stick as long as it is not disturbed. However, when any strain is placed on the butter (as with a butter knife), the butter loses strength so that it can be easily spread. In that way, brittle behavior and static liquefaction are types of strain-softening behavior.

According to Robertson et al. (2019), the presence of iron oxide bonding results in a particularly acute degree of brittle or strain-softening behavior. Fig. A12 compares the strength loss with and without iron oxide bonding. The iron oxide bonds increase the initial stiffness of the tailings, meaning that a small increase in strain causes a larger increase in stress (see Fig. A12). The iron oxide bonding results in a higher peak strength and then a lower residual strength after the stress has exceeded the peak strength, so that the total strength loss is greater (see Fig. A12). Finally, the iron oxide bonding causes a more sudden transition from the stiff behavior to the strain-softening behavior. In a visual way, with iron oxide bonding, the curve of strength as a function of strain is sharper and less rounded (see Fig. A12).

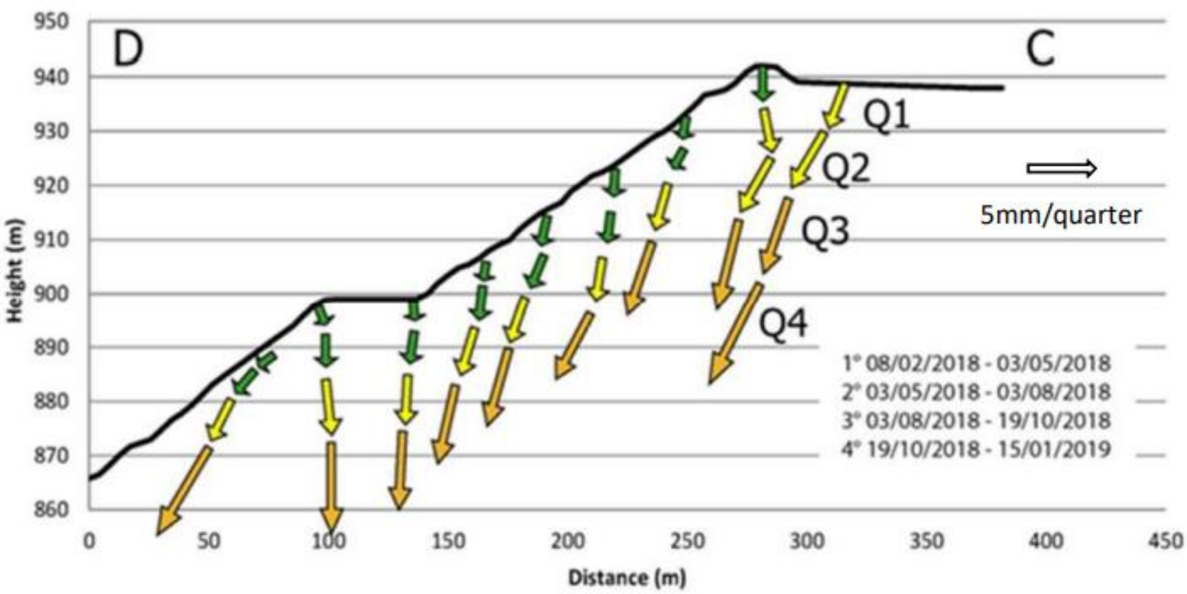

Figure 20: Cross-section Showing Deformation Vectors for the Four Quarters Prior to Failure

Figure A11. The downward creep of tailings due to gravity in the year preceding the failure of the Brumadinho tailings dam caused an increase in the shear stress on the iron oxide bonds between the tailings (see Figs. A10a-b). Because of the brittle nature of the iron oxide bonds, a small strain caused a large increase in shear stress (see Fig. A12). Figure from Robertson et al. (2019).

A second forensics team re-examined the cause of failure of the tailings dam at Brumadinho and came to a different set of conclusions (CIMNE, 2021). It is important to consider where the two teams agreed and where they disagreed. Both teams agreed that the cause of failure of the tailings dam was static liquefaction. However, the CIMNE (2021) team concluded that the proximal event that triggered the static liquefaction was not the combination of downward creep and heavy rainfall, but the high-pressure drilling of a borehole near the dam crest for the installation of monitoring instrumentation at the time of dam failure. Moreover, CMINE (2021) did not agree that the formation of iron oxide bonds was a significant factor contributing to the failure of the tailings dam. According to CIMNE (2021), "We have not found evidence for any significant bonding in the tailings, independently of their grading. The undrained brittleness in the tailings is not a consequence of bonding."

On the other hand, both Robertson et al. (2019) and CIMNE (2021) agreed that the brittle behavior of the tailings was a critical factor in the events leading to static liquefaction, as even seen in the preceding quote. According to CIMNE (2021), "The tailings were not homogenous. There were finer and coarser gradings. Finer gradings had lower permeabilities and more contractive structures … finer gradings also had lower capacity of mobilizing strength in undrained conditions … Consequently, finer gradings were more prone to liquefaction and more dangerous, because more brittle." Although CIMNE (2021) did not agree that iron oxide bonding had caused the brittle behavior of the iron-ore tailings, they did not offer any alternative for understanding the origin of brittle behavior at the granular level.

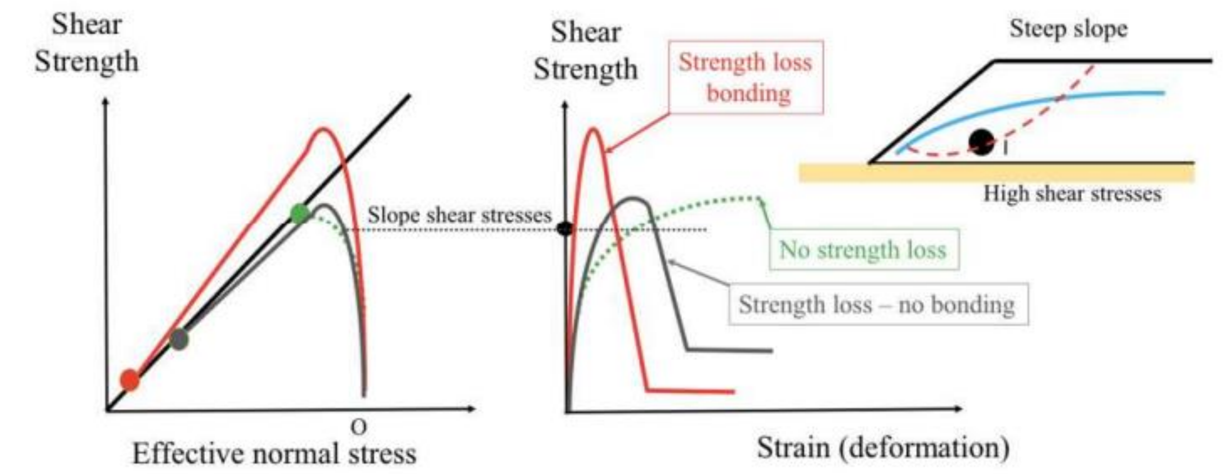

Figure 49: Schematic Comparison in Behavior Between Soil that has No Strength Loss, Soil with Strength Loss, and Either No Bonding or with Bonding

Figure A12. Iron oxide bonding between tailings results in highly brittle behavior. The bonds are stiff so that a small amount of strain causes a large increase in shear stress on the bonds. A small additional shear stress (equivalent to a small additional strain) can then cause the bonds to break with a large strength loss (decrease in shear stress). If no iron oxide bonding is present, the tailings are less brittle. There is a smaller increase in shear stress for a given strain, the peak (or yield) shear strength occurs at a higher strain, and there is a smaller strength loss when the peak strength is exceeded. Materials that exhibit no strength loss (materials that are not strain softening) show steadily increasing shear stress with increasing strain. Figure from Robertson et al. (2019).

At the present time, no other published study has addressed the question as to whether iron-ore tailings have a propensity for brittle behavior or whether the brittle behavior of iron-ore tailings results from the formation of iron oxide bonds between the tailings. Alonso (2021) and Martí et al. (2021) re-examined the failure of the tailings dam at Aznalcóllar in Spain in 1998 and concluded that the failure resulted from the brittle behavior of the clays in the dam foundation. On the other hand, the investigation into the cause of failure of the upstream Fundão tailings dam at the Samarco iron-ore mine in 2015 (Morgenstern et al., 2016) drew attention to the large strength loss (equivalent to brittle behavior) of the iron-ore tailings that occurred after liquefaction (see Fig. A13). Like CIMNE (2021), Morgenstern et al. (2016) did not consider the origin of brittle behavior, but regarded brittle behavior only as a measurement.

By way of clarification, the phrase "undrained brittleness" (CIMNE, 2021) refers to brittle behavior that occurs under the undrained condition, which is the condition under which water cannot escape from pores during deformation, either due to low permeability or the speed of the deformation. The undrained condition also requires saturation of the pores or the near saturation of the pores prior to deformation (because the deformation itself can induce saturation by constricting the pores). The opposite is the drained condition under which water is free to escape from pores during deformation either because of high permeability, the low speed of the deformation, or the low water content of the pores. Typically, tailings and other materials will have different shear strength parameters depending upon whether deformation occurs in the drained or undrained condition. Finally, the phrase “undrained strength ratio” in Fig. A13 refers to the ratio of the undrained strength of the tailings to the effective normal (vertical) stress (see Fig. A3). The concepts of undrained and drained strength and deformation conditions will be further developed in the subsection Post-Brumadinho Guidance on Brittle Tailings: Implications for Upstream Dams.

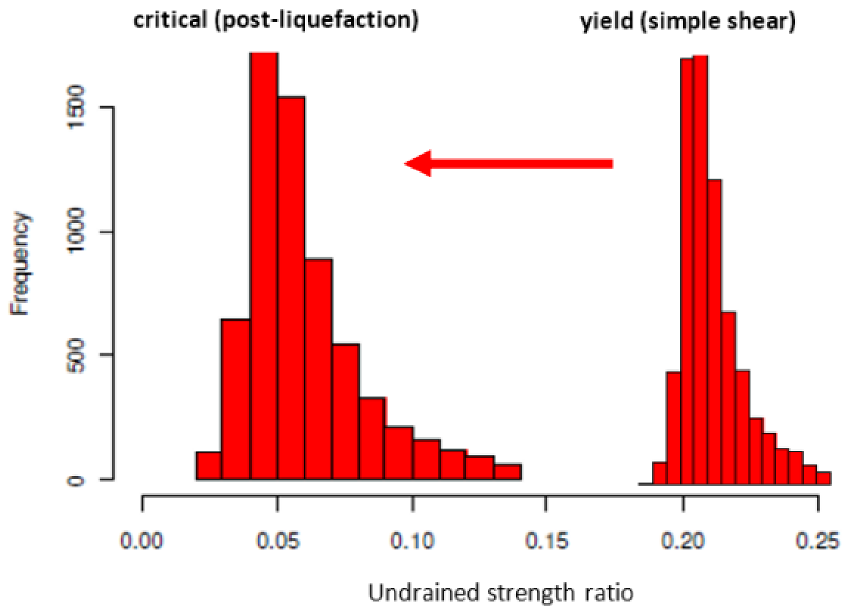

Figure 4-6 Yield (pre-flowslide) and critical (post-flowslide) undrained strengths for aggregated 2015 Fundão CPT data

Figure A13. Based on a comparison of the mean yield (peak) strength ratio of 0.21 and the critical (post-liquefaction or liquefied or residual) strength ratio of 0.07 (Morgenstern et al., 2016), the strength loss index of the iron-ore tailings at the failed Fundão tailings dam at the Samarco mine was 0.67, which would be classified as “highly brittle” according to the upcoming ICOLD bulletin (see Fig. A18a; Ridlen, 2021). Morgenstern et al. (2016) did not investigate the formation of iron oxide bonds between the tailings as a possible cause of brittle behavior. No other study since Robertson et al. (2019) has examined the propensity of iron-ore tailings to exhibit brittle behavior. However, based on the reviews of tailings dam failures at iron-ore mines by Morgenstern et al. (2016) and Robertson et al. (2019), at the present time, brittle behavior should be suspected in all iron-ore tailings. Figure from Morgenstern et al. (2016).

Emerging Tailings Dam Databases

The analysis of this Appendix relies heavily on three tailings dam databases that have become available only over the last three years, which are a database on global tailings dam failures (Center for Science in Public Participation, 2022), a database on global tailings dams (GRID-Arendal, 2022), and a national databases for tailings dams in the USA (USACE, 2022). At the present time, national tailings dam databases also exist for tailings dams in Brazil (ANM, 2022), Chile (SNGM, 2020), Mexico (Secretaría de Medio Ambiente y Recursos Naturales (México) [Secretariat of Environment and Natural Resources (Mexico)], 2022), Peru (CooperAcción, 2022), and Spain (Rodríguez Pacheco and Gómez De Las Heras, 2006; IGME, 2022). The database Tailings Dam Failures 1915-2020 lists 351 tailings dam failures and, as of this writing, is up-to-date as of June 6, 2020 (Center for Science in Public Participation, 2022). Tailings Dam Failures 1915-2020 replaces an older database (ICOLD and UNEP, 2001) and is more complete than WISE (2022). Tailings Dam Failures 1915-2020 should also be regarded as incomplete and is especially incomplete with regard to the available information about each tailings dam failure. Based on the nationalities of the compilers, the database is probably more complete for the USA and other English-speaking countries.

In addition to other information, Tailings Dam Failures 1915-2020 (Center for Science in Public Participation, 2022) lists the dam type, dam height, storage volume, release volume, and severity code for each failure. Out of the 351 tailings dam failures, tailings dam types are listed as US (Upstream), CL (Centerline) and DS (Downstream) for 106 failures, 14 failures, and 30 failures, respectively (Center for Science in Public Participation, 2022). The above dam types probably do not include tailings dams that combine different types of raises, since the database also includes such types as “DS then US” and “US/CL.” For the USA alone, Tailings Dam Failures 1915-2020 (Center for Science in Public Participation, 2022) includes 117 tailings dam failures. This observation suggests that the USA is much better represented in the database than other countries, since it is not likely that the USA has accounted for 33% of all global tailings dam failures. For the USA, tailings dam types are listed as US (Upstream), CL (Centerline) and DS (Downstream) for 34 failures, 9 failures, and 12 failures, respectively.

Tailings Dam Failures 1915-2020 (Center for Science in Public Participation, 2022) includes four choices for the severity code. A Very Serious Tailings Dam Failure indicates “multiple loss of life and/or release of ≥ 1,000,000 m^3 tailings and/or tailings travel of 20 km or more” (Center for Science in Public Participation, 2022). A Serious Tailings Dam Failure indicates “loss of life and/or release of ≥ 100,000 m^3 tailings” (Center for Science in Public Participation, 2022). Other Tailings Dam Failure indicates “engineering/facility failure other than those classified as Very Serious or Serious, no loss of life” (Center for Science in Public Participation, 2022). Finally, a Waste-Related Accident is not a failure in the tailings dam itself, but includes “related facility tailings failures (e.g. sinkholes, pipelines), and non-tailings incidents (e.g. mine plug failures, waste rock failures, etc.)” (Center for Science in Public Participation, 2022).

The most complete database for existing tailings dams in the USA is contained within the National Inventory of Dams, which was first released by the U.S. Army Corps of Engineers in January 2019 and last partially updated in March 2020 (USACE, 2022). The National Inventory of Dams relies upon data provided by state and federal dam regulators and includes over 90,000 dams, of which 1402 are tailings dams. Among other information, the database includes dam height and storage capacity, but not the current storage volume nor the method of construction. The database does include dam type, but this largely refers to the material out of which the dam was constructed, the choices including Unknown, Arch, Concrete, Earth, Other and Rockfill. Out of the 1402 tailings dams, 1139 (81.2%) were constructed from earth (which must include tailings), 20 (1.4%) were constructed from rockfill (which probably includes waste rock), while only two were constructed out of concrete. The information in the National Inventory of Dams is not entirely up-to-date, since, for example, it lists Dam 2 of the Mile Post 7 tailings storage facility in Minnesota has still having a height of only 45 feet, compared to the current height of 84 feet (based upon a comparison of the crest elevation given in Minnesota Department of Natural Resources (2021) and the toe elevation given in Barr Engineering (2019)).

The most complete database for existing tailings dams in Brazil is the *Sistema Integrado de Gestão de Barragens de Mineração* [Integrated Management System for Mining Dams]

(ANM, 2022), which includes data for 910 tailings dams. Among other information, the database lists the method of construction, the current height, and the current storage volume, but not the planned storage volume nor the storage capacity. The most complete database for existing tailings dams in Chile is the *Depósito de Relaves—Catastro de Depósitos de Relaves en Chile (actualización 10-08-2020)* [Tailings Deposit—Registry of Tailings Deposits in Chile (update August 10, 2020), which includes 757 tailings dams (SNGM, 2020). Among other information, the database lists the method of construction, the current storage volume, and the authorized storage volume, but not the height. Tailings dam databases for Mexico (Secretaría de Medio Ambiente y Recursos Naturales (México) [Secretariat of Environment and Natural Resources (Mexico)], 2022), Peru (CooperAcción, 2022), Peru, and Spain (Rodríguez Pacheco and Gómez De Las Heras, 2006; IGME, 2022) list 585, 417, and 988 tailings dams, respectively, but do not include information on method of construction, height, current storage volume, or storage capacity. All of the preceding national databases are maintained by governmental agencies, except in Peru, where the national database is maintained by the non-governmental organization CooperAcción.

The most complete database for existing global tailings dams is the Global Tailings Portal, which currently includes 2055 tailings dams (GRID-Arendal, 2022). The Global Tailings Portal was developed from questionnaires that were sent to 727 publicly-listed mining companies by the Investor Mining and Tailings Safety Initiative in 2019. By December 2019, 332 mining companies had responded, of which about 100 provided information about tailings storage facilities. By January 2020, 60 companies had verified the information in the Global Tailings Portal. Franks et al. (2021) published an analysis of the data in the Global Tailings Portal and included a spreadsheet with the 1743 tailings dams for which information was available at the time of their analysis. Since it is not currently possible to download a spreadsheet from the website of the Global Tailings Portal (GRID-Arendal, 2022), the analysis of this report will refer to the spreadsheet available as Supplementary Information with Franks et al. (2021).

Just as with the other databases, the Global Tailings Portal cannot be regarded as complete. The completeness of the Global Tailings Portal can be partially assessed by comparing the number of tailings dams in the portal with the number of tailings dams in each of the preceding national databases. The percentage recovery in the Global Tailings Portal is very uneven, since the number of tailings dams is 149 (16.4%), 34 (4.5%), 39 (6.7%), 77 (18.5%), 4 (0.4%), and 235 (16.8%) for Brazil, Chile, Mexico, Peru, Spain and the USA, respectively. The Global Tailings Portal is very deficient in some areas, including, for example, only four tailings dams in China. Based on the above, a reasonable estimate for the number of global tailings dams might be in the range 20,000-30,000, so that the Global Tailings Portal includes less than 10% of the global inventory.

At the same time, the Global Tailings Portal cannot be regarded as a subset of the existing national databases for Brazil, Chile, Mexico, Peru, Spain, and the USA. In fact, for some states of the USA, the Global Tailings Portal (GRID-Arendal, 2022) lists more tailings dams than the National Inventory of Dams (USACE, 2022). For example, the Global Tailings Portal lists three tailings dams for Minnesota, while the National Inventory of Dams includes 56 tailings dams for Minnesota. By contrast, the Global Tailings Portal lists 21 tailings dams in Colorado with only seven tailings dams in the National Inventory of Dams. The preceding discrepancies reveal relative differences in the ability and willingness of regulators and mining companies to provide information about tailings dams on a state-by-state basis in the USA.

Among other information, the Global Tailings Portal includes the current height, the current tailings storage, the planned tailings storage (within five years), the raise type, the raise category, the age of the tailings storage facility, and the history of stability concerns. The six categories under Raise Category include Centreline, Downstream, Dry Stack, Hybrid, In-pit/Landform, Single-stage, Upstream, Other and Unknown. "Modified Centreline" is a type of Raise Type. In all 18 cases, the Raise Type "Modified Centreline" corresponds to the Raise Category "Hybrid." Franks et al. (2021) explained that "the term 'hybrid' facility is used here to refer to facilities where multiple raise methods are utilised in the same facility over time," but that "for data analysis purposes Modified Centreline facilities were categorized together with Centreline facilities." 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). Further information about the tailings dam databases will be provided in the subsections Post-Brumadinho Guidance and Data on Upstream Dams and Effect of Height on Risk of Failure of Tailings Dams.

Post-Brumadinho Guidance and Data on Upstream Dams

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). The guidance document Safety First: Guidelines for Responsible Mine Tailings Management also called for a ban on new upstream dams and the safe closure of existing upstream dams and added that “the deadline for safe closure must depend primarily on engineering, rather than economic considerations” (Morrill et al., 2020). Morrill et al. (2020) critiqued the earlier work by Martin et al. (2002) in writing, “It is theoretically possible to safely construct and operate an upstream tailings dam under the limited conditions of low seismicity and low precipitation. 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 a broad consensus within the engineering community 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.” Hopkins and Kemp (2021) wrote, “We can only agree with Earthworks and MiningWatch Canada [publishers of Morrill et al. (2020)] on this matter” and repeated the preceding quote.

Other 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 (2019b), “It is recommended that upstream constructed tailings dams not be built in high seismic areas.” According to ICOLD (2021), “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).

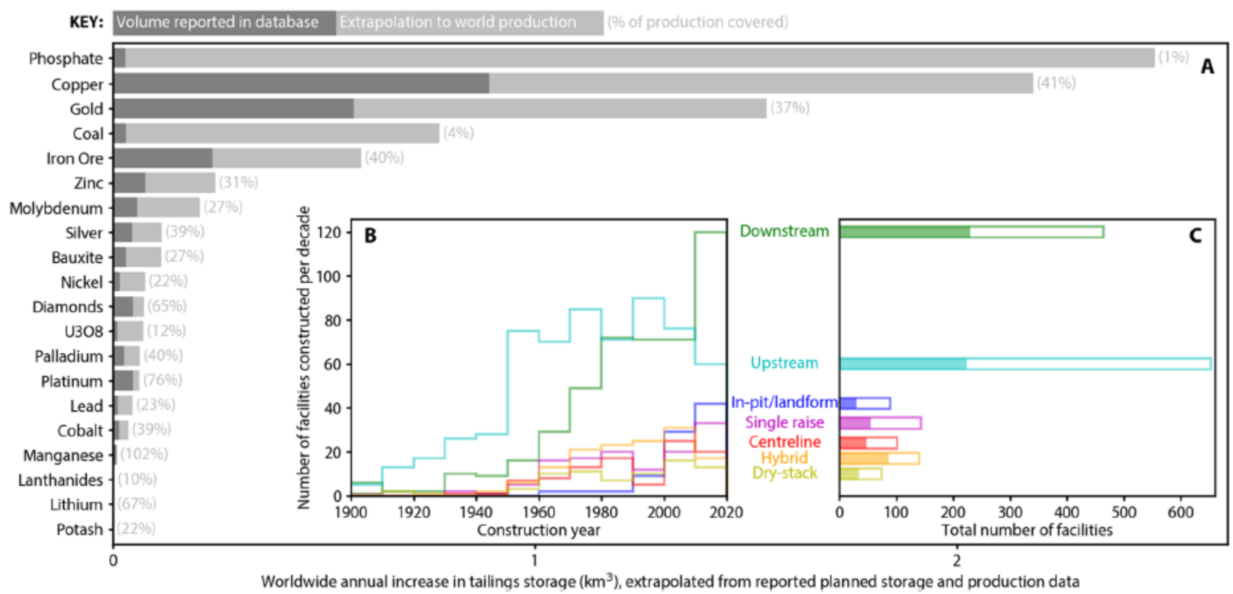

Figure 1. Tailings storage. (**A**) Tailings storage volume increase per year over the 2019–2023 period for a range of commodities as reported in the dataset and extrapolated to world production. (**B**) Number of reported facilities constructed per decade by raise type. (**C**) Reported tailings facilities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

Figure A14. 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 analysis of the Global Tailings Portal (GRID-Arendal, 2022) 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. A14). 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. A14). 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. A14). 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).

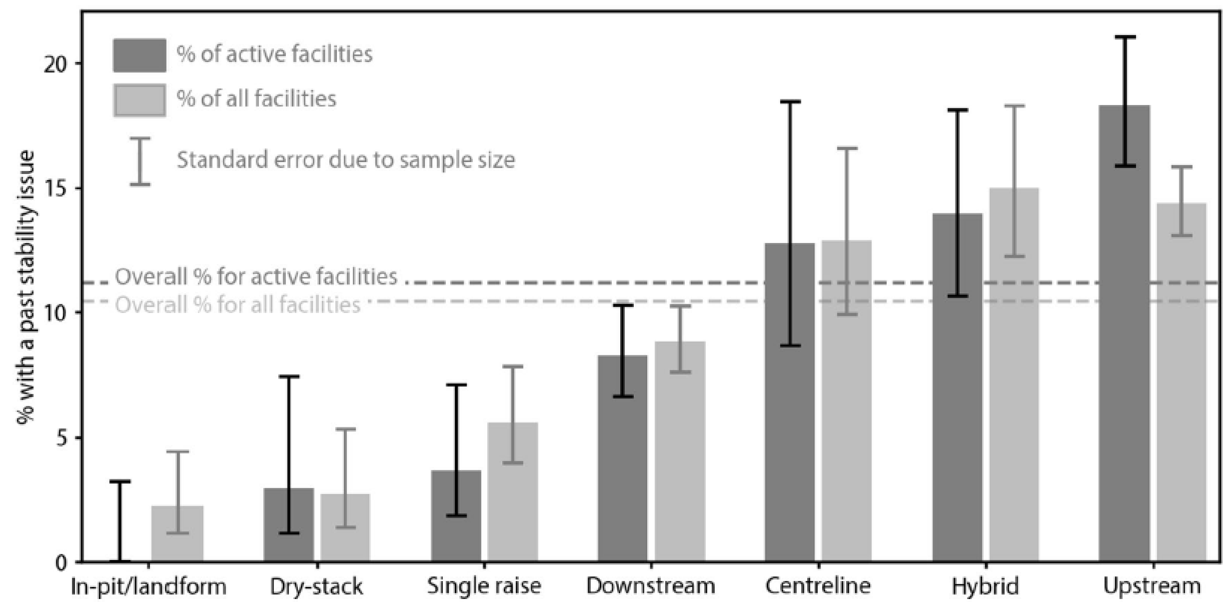

Figure 3. Stability of tailings facilities. Proportion of facilities with a stability issue by raise type. Error bar lengths are binomial confidence intervals for the subsample represented by each bar, showing ± 1 standard error (approximately 68%).

Figure A15. 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).

Franks et al. (2021) also established that upstream dams have increased stability issues, even in cases where the stability issues did not proceed to dam failure (see Fig. A15). 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 greater risk of failure of upstream dams is also evident in their disproportionate representation in the database of tailings dam failures (Center for Science in Public Participation, 2022), in comparison to the database of existing tailings dams (GRID-Arendal, 2022). The Global Tailings Portal includes 653 upstream dams, 101 centerline dams, and 464 downstream dams, totaling 1218 dams for which construction is known to be either upstream, centerline or downstream (not including hybrid dams, single-stage dams, etc.) (see Table A2a). The database Tailings Dam Failures 1915-2020 includes 106 upstream dams, 14 centerline dams, and 30 downstream dams, totaling 150 dams for which construction is known to be either upstream, centerline or downstream (see Table A2a). Thus, upstream dams constitute 70.7% of tailings dam failures, but only 53.6% of existing tailings dams (see Table A2a). By contrast, downstream dams constitute 20.0% of tailings dam failures, but 38.1% of existing tailings dams (see Table A2a). The pattern seems less clear when restricted to tailings dams in the USA in both databases. For just the USA, centerline dams are disproportionately represented with 16.4% of tailings dam failures and 7.2% of existing tailings dams (see Table A2b). The less-clear pattern may just result from the much smaller dataset when restricted to the USA, with 55 tailings dam failures and 181 existing tailings dams for which the construction method is either upstream, centerline or downstream (see Table A2b). It should be recalled that the National Inventory of Dams (USACE, 2022) cannot be used for this exercise because it does not include methods of construction.

Table A2a. Comparison of failure proportions for tailings dam construction methods: Global

Construction Method	Failed Tailings Dams[1]	Existing Tailings Dams[2]
Upstream	106 (70.7%)	653 (53.6%)
Centerline	14 (9.3%)	101 (8.3%)
Downstream	30 (20.0%)	464 (38.1%)
Total	150 (100.0%)	1218 (100.0%)

[1]Failed tailing dams taken from database in Center for Science in Public Participation (2022) that states US (Upstream), CL (Centerline), or DS (Downstream) under the heading "Dam Type." The complete database includes 351 tailings dam failures from 1915 to 2020.

[2]Existing tailings dams taken from database in Global Tailings Portal (GRID-Arendal, 2022) that states Upstream, Centreline, or Downstream under the heading "Raise Category." The complete database lists 1743 existing tailings dams.

Table A2b. Comparison of failure proportions for tailings dam construction methods: USA

Construction Method	Failed Tailings Dams[1]	Existing Tailings Dams[2]
Upstream	34 (61.8%)	120 (66.3%)
Centerline	9 (16.4%)	13 (7.2%)
Downstream	12 (21.8%)	48 (26.5%)
Total	55 (100.0%)	181 (110.0%)

[1]Failed tailing dams taken from database in Center for Science in Public Participation (2022) that states US (Upstream), CL (Centerline), or DS (Downstream) under the heading "Dam Type." The complete database includes 117 tailings dam failures in the USA from 1940 to 2018.

[2]Existing tailings dams taken from database in Global Tailings Portal (GRID-Arendal, 2022) that states Upstream, Centreline, or Downstream under the heading "Raise Category." The complete database lists 235 existing tailings dams in the USA.

Table A3a. Comparison of failure severity for tailings dam construction methods: Global[1]

Severity Code[2]	Construction Methods		
	Upstream	**Centerline**	**Downstream**
Very Serious Tailings Dam Failure	20 (18.9%)	1 (7.1%)	3 (10.0%)
Serious Tailings Dam Failure	22 (20.8%)	1 (7.1%)	5 (16.7%)
Other Tailings Dam Failure	62 (58.5%)	11 (78.6%)	18 (60.0%)
Waste-Related Accident	2 (1.9%)	1 (7.1%)	4 (13.3%)
Total	106 (100.0%)	14 (100.0%)	30 (100.0%)

[1]Failed tailing dams taken from database in Center for Science in Public Participation (2022) that states US (Upstream), CL (Centerline), or DS (Downstream) under the heading "Dam Type." The complete database includes 351 tailings dam failures from 1915 to 2020.
[1]Severity codes from Center for Science in Public Participation (2022):
Very Serious Tailings Dam Failure = multiple loss of life and/or release of ≥ 1,000,000 m^3 tailings and/or tailings travel of 20 km or more
Serious Tailings Dam Failure = loss of life and/or release of ≥ 100,000 m^3 tailings
Other Tailings Dam Failure = engineering/facility failure other than those classified as Very Serious or Serious, no loss of life
Waste-Related Accident = related facility tailings failures (e.g. sinkholes, pipelines), and non-tailings incidents (e.g. mine plug failures, waste rock failures, etc.)

Table A3b. Comparison of failure severity for tailings dam construction methods: USA[1]

Severity Code[2]	Construction Methods		
	Upstream	**Centerline**	**Downstream**
Very Serious Tailings Dam Failure	3 (8.8%)	1 (11.1%)	0 (0.0%)
Serious Tailings Dam Failure	9 (26.5%)	1 (11.1%)	1 (8.3%)
Other Tailings Dam Failure	22 (64.7%)	6 (66.7%)	8 (66.7%)
Waste-Related Accident	0 (0.0%)	1 (11.1%)	3 (25.0%)
Total	34 (100.0%)	9 (100.0%)	12 (100.0%)

[1]Failed tailing dams taken from database in Center for Science in Public Participation (2022) that states US (Upstream), CL (Centerline), or DS (Downstream) under the heading "Dam Type." The complete database includes 117 tailings dam failures in the USA from 1940 to 2018.
[2]Severity codes from Center for Science in Public Participation (2022):
Very Serious Tailings Dam Failure = multiple loss of life and/or release of ≥ 1,000,000 m^3 tailings and/or tailings travel of 20 km or more
Serious Tailings Dam Failure = loss of life and/or release of ≥ 100,000 m^3 tailings
Other Tailings Dam Failure = engineering/facility failure other than those classified as Very Serious or Serious, no loss of life
Waste-Related Accident = related facility tailings failures (e.g. sinkholes, pipelines), and non-tailings incidents (e.g. mine plug failures, waste rock failures, etc.)

Tailings dam risk includes both the likelihood and the consequences of tailings dam failure. In this respect, upstream dams are over-represented in terms of both Very Serious and Serious tailings dam failures. On a global basis (including the USA) and using the same databases (Center for Science in Public Participation, 2022; GRID-Arendal, 2022), 18.9% and 20.8% of failures of upstream tailings dams are Very Serious and Serious, respectively (see Table A3a). By contrast, 10.0% and 16.7% of failures of downstream tailings dams are Very Serious and Serious, respectively (see Table A3a). In summary form, on a global basis, 39.7% of failures of upstream dams are Very Serious or Serious, while 26.7% of failures of downstream dams are Very Serious or Serious (see Table A3a). The pattern becomes even starker when tailings dam failures are restricted to the USA. For the USA alone, 8.8% and 26.5% of failures of upstream tailings dams are Very Serious or Serious, respectively, summing to 35.3% (see Table A3b). By contrast, 0.0% and 8.3% of failures of downstream tailings dams are Very Serious or Serious, respectively (see Table A3b). As this report was being completed, Piciullo et al. (2022) appeared, which reached similar conclusions regarding the disproportionate probability of failure and consequences of failure for upstream tailings dams.

Post-Brumadinho Guidance on Brittle Tailings: Implications for Upstream Dams

Much of the industry guidance that has emerged since the Brumadinho disaster has focused on the extra caution required for the safe storage of brittle tailings. According to new guidance from the International Council on Mining & Metals (ICMM), "The stability of the tailings embankments and abutments may be impacted by: • The presence of brittle materials, either within the embankment, abutment, or foundation of the embankment, that could lead to the rapid loss of shear strength. • The development of static liquefaction due to rapid construction loading or the development of undrained loading conditions in brittle materials at the onset of yield … Brittle materials in either the embankment or the foundation require special consideration inclusive of design and construction based upon either lower bound strengths (e.g. assume the brittleness is triggered) or sufficient robustness to prevent the sudden loss of strength from ever occurring" (ICMM, 2021).

ICMM (2021) was especially critical of the use of single-valued criteria, such as the factor of safety (lowest ratio of shear strength to applied shear stress as considered over all possible failure surfaces), to assess the stability of a tailings storage facility where brittle tailings are stored or where brittle failure modes (liquefaction) are possible. ICMM (2021) 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."

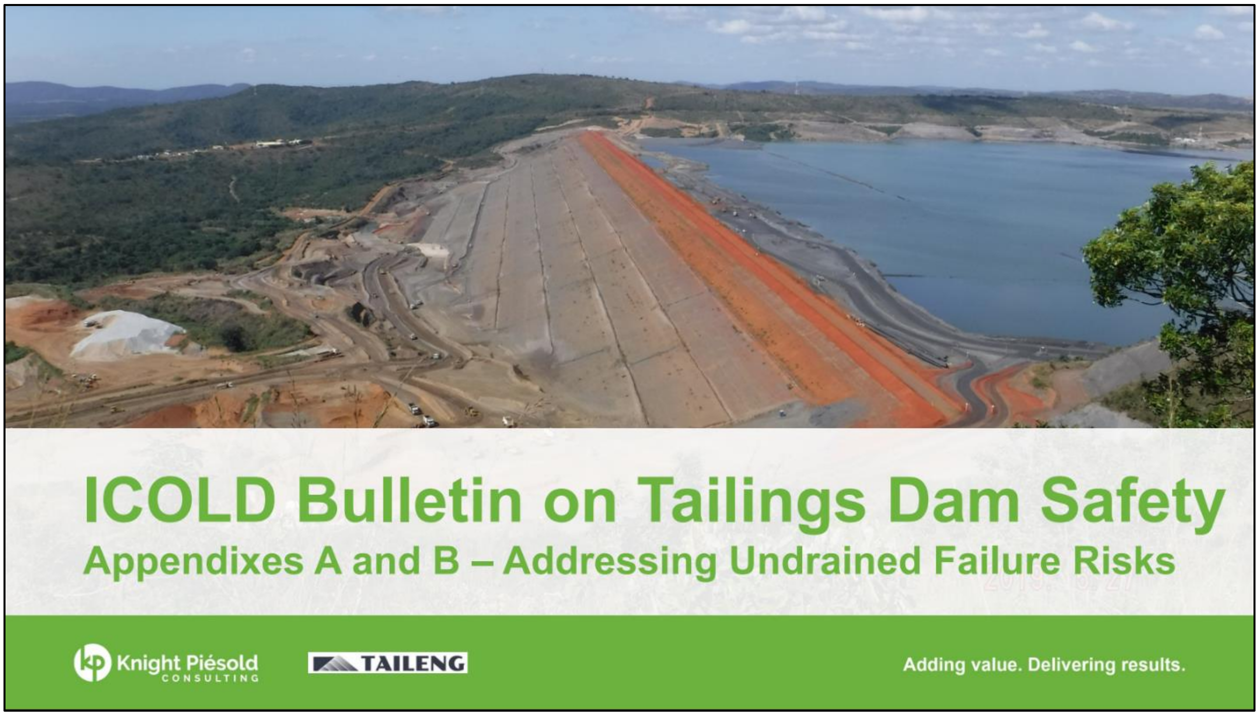

Figure A16. On December 8, 2021, Paul Ridlen gave a presentation entitled "ICOLD Bulletin on Tailings Dam Safety—Appendices A and B – Addressing Undrained Failure Risks" as Lecture 7 of the online course EGLL 2023 Static and Cyclic Liquefaction of Mine Tailings through Colorado State University. The ICOLD bulletin is scheduled for release following the ICOLD conference in June 2022. Paul Ridlen is a member of the Working Group of the bulletin and one of the three authors of Appendices A and B. Slide from Ridlen (2021).

The most significant new industry guidance on brittle tailings is the upcoming ICOLD Bulletin on Tailings Dam Safety—Appendices A and B – Addressing Undrained Failure Risks, which is scheduled for release following the ICOLD conference in Marseilles, France, in June 2022 (see Fig. A16). On December 8, 2021, Paul Ridlen, a member of the Working Group of the bulletin and one of the three authors of Appendices A and B, gave a presentation on the upcoming bulletin as Lecture 7 of the online course EGLL 2023 Static and Cyclic Liquefaction of Mine Tailings through Colorado State University (Ridlen, 2021). The author of this report was a registered student in that course, for which PowerPoint presentations were provided with no requirement or request for confidentiality.

The upcoming ICOLD bulletin elaborates on the discussion in Robertson et al. (2019) in pointing out that brittle behavior is a special category of strain-softening behavior in which there is a substantial loss of strength once the peak (yield) strength has been exceeded (see Curve F in Fig. A17). Other strain-softening materials might show only a slight loss of strength (see Curve C in Fig. A17), 25% strength loss (see Curve E in Fig. A17) or 40% strength loss (see Curve D in Fig. A17). Strain-hardening materials show progressive increase in shear stress with increasing strain (see Curve B in Fig. A17), while in a plastic material, deformation occurs at constant shear stress independent of the strain (see Curve A in Fig. A17).

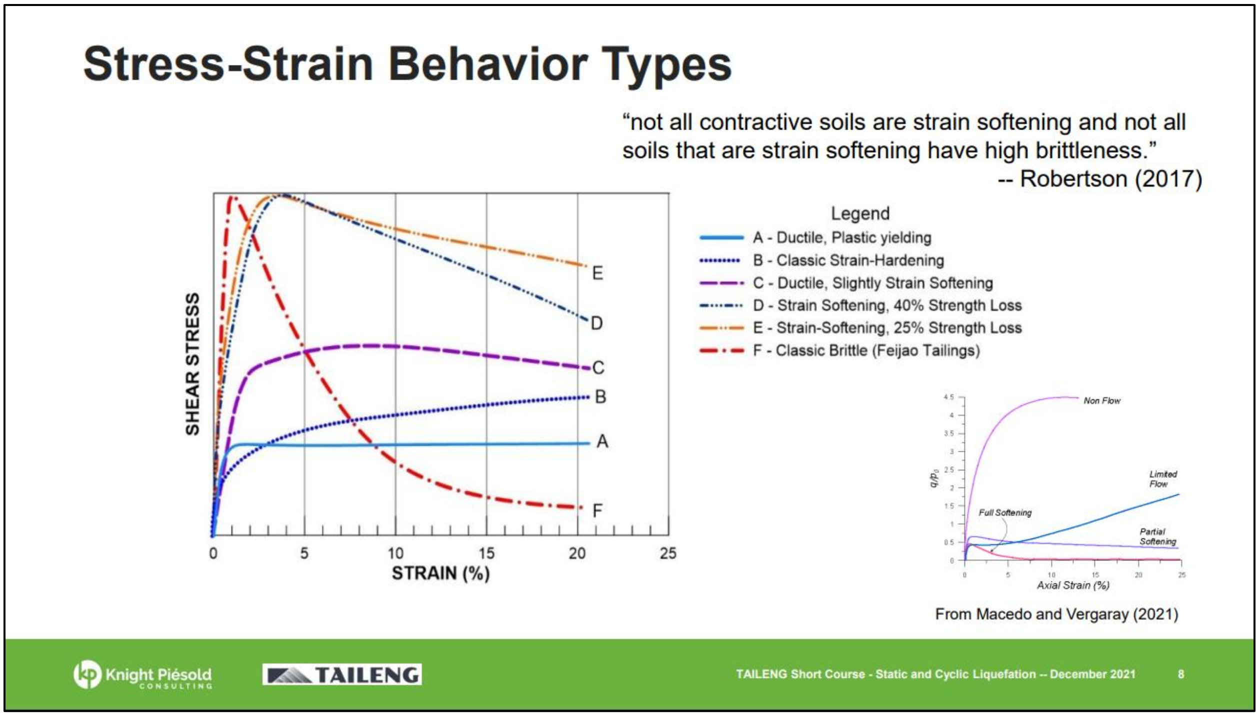

Figure A17. In a strain-softening material, the shear stress decreases for strains greater than some critical strain (or corresponding peak shear strength). Brittle materials are a special class of strain-softening materials in which there is a substantial loss of shear strength after the peak shear strength has been exceeded (see Curve F in figure above). Curves C, D and E also show strain-softening behavior, but with lesser strength loss. Strain-hardening materials show progressive increase in shear stress with increasing strain (see Curve B in figure above). In a plastic material, deformation occurs at constant shear stress independent of the strain (see Curve A in figure above). Slide from Ridlen (2021).

The upcoming ICOLD bulletin follows Bishop (1967, 1973) in defining the strength loss index I_B as

$$I_B = \frac{\tau_p - \tau_r}{\tau_p}$$

where τ_p is the peak (yield) undrained strength and τ_r is the residual (liquefied) undrained strength (see Fig. A18a). The bulletin then classifies as "highly brittle" any materials for which $I_B > 0.4$ or any materials for which $I_B > 0.2$ as long as they reach a peak shear strength at 3% strain or less and lose more than 20% of the peak strength prior to reaching 10% strain (see Fig. A18a). For comparison, according to Macedo and Vergeray (2021), "The trends suggest that flow liquefaction cases with partial softening may have in general a I_B larger than 0.25 … whereas the flow liquefaction cases with full softening may be associated with I_B values higher than 0.6" (see Fig. A18b). The upcoming ICOLD bulletin points out that it is difficult to accurately measure both the peak (yield) strength and the residual (liquefied or post-liquefaction) strength, so that there is considerable uncertainty in the strength loss index. According to the bulletin, "ICOLD cautions that these indicative or screening criteria must be applied with a high level of engineering judgment and scrutiny, especially when brittleness and the potential for flow (static) liquefaction are being ruled out" (see Fig. A19; Ridlen, 2021). The upcoming ICOLD bulletin is essentially saying that brittle behavior should be assumed as a default, unless there is substantial evidence to the contrary.

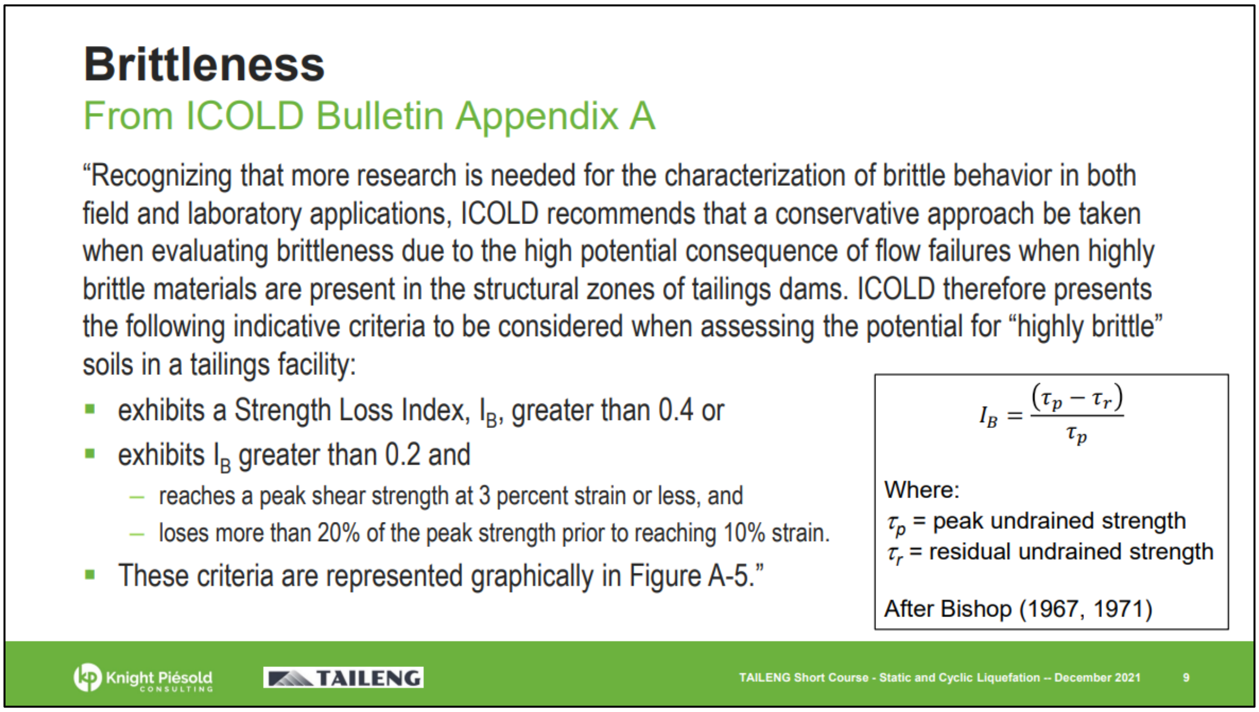

Figure A18a. The upcoming ICOLD bulletin defines a "highly brittle" material as a material with a strength loss index greater than 0.4. Slide from Ridlen (2021).

The most important sentence in the upcoming ICOLD bulletin states that **"Brittle materials should never be allowed in the structural zones of new facilities"** (boldface in the original) (see Fig. A20, Ridlen, 2021). For full comprehension, it is important to note that brittleness is a possible state of a material, not an essential property of a material. Granular materials (such as soils or tailings) can be either contractive or dilative. Contractive materials will tend to compress or consolidate when they are disturbed (see Fig. A4). Dilative materials will tend to expand when they are disturbed. Thus, the same material can be either contractive or dilative, depending upon whether it is loosely-packed (see Fig. A4) or densely-packed. Granular materials can undergo liquefaction only if they are loosely-packed or in the contractive state. Granular materials that will neither compress nor expand when they are disturbed are said to be in the critical state. Thus, the boldface sentence means that the structural zone should never include materials that would be brittle if they were in the contractive state. Such materials should be allowed in the structural zone only if they can be adequately compacted into the dilative state.

The implication of the combination of ICOLD Bulletin 181 (ICOLD, 2021) and the upcoming ICOLD bulletin (Ridlen, 2021) is that the storage of brittle tailings in upstream tailings storage facilities is highly problematic. ICOLD (2021) clarifies that the structural zone includes the stack of beaches or essentially any tailings that would underlie the dikes (see Fig. A8). The upcoming ICOLD bulletin (Ridlen, 2021) states that the structural zone should never contain brittle tailings. Compliance with both bulletins would be possible only if all sand-sized tailings that were hydraulically discharged from the dam crest and which settled close to the dam crest to form a beach (see Fig. A1) found themselves to be in the dilative state. These beach tailings cannot be compacted by machine because they are too wet (see Fig. A1). Thus, the succession of beach tailings can be in the dilative state only if the tailings adequately drained (so that they were unsaturated) and only if they could be compacted into the dilative state by the weight of the overlying dikes and tailings. Thus, compliance with both bulletins seems to be only a remote possibility. Moreover, if post-deposition testing showed that the beach tailings had not been compacted into a dilative state, there seems to be no way to repair the situation. Based upon contemporary industry guidance, at the present time, the safe storage of brittle tailings in upstream tailings storage facilities should be regarded as impossible.

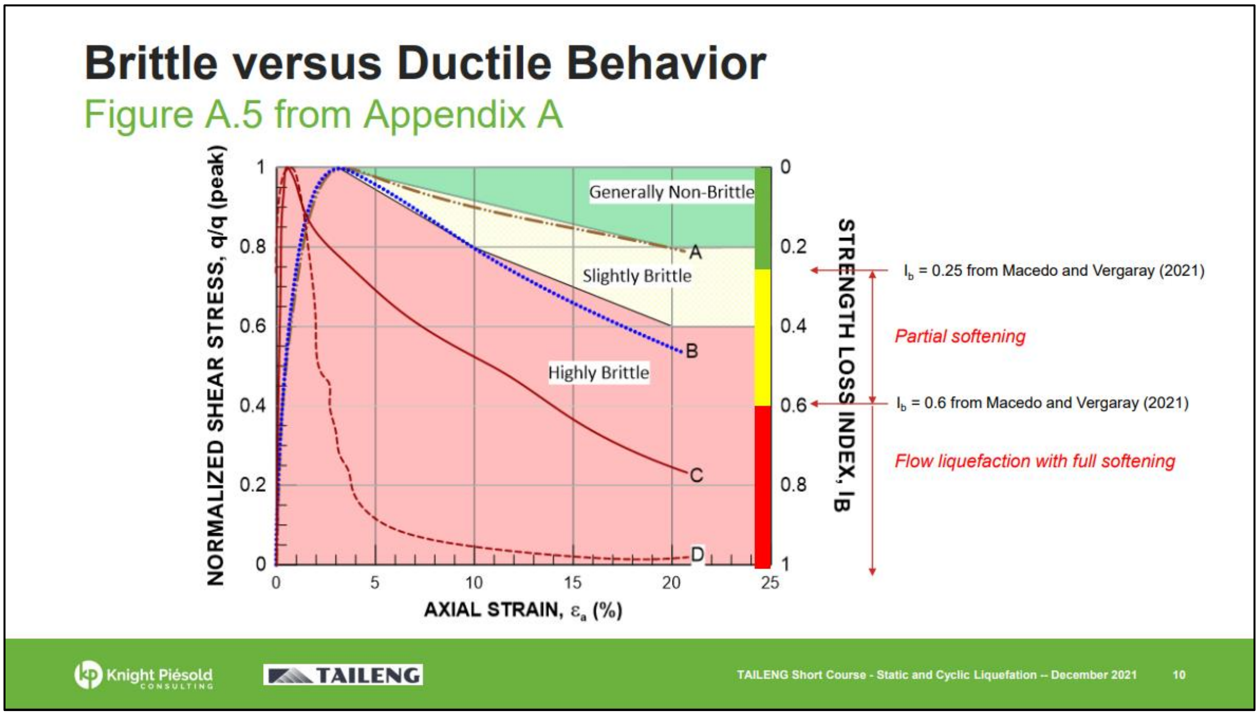

Figure A18b. The upcoming ICOLD bulletin defines a "highly brittle" material as a material with a strength loss index (I_B) greater than 0.4 (see Fig. A18a). According to Macedo and Vergeray (2021), "The trends suggest that flow liquefaction cases with partial softening may have in general a I_B larger than 0.25 … whereas the flow liquefaction cases with full softening may be associated with I_B values higher than 0.6." Slide from Ridlen (2021).

Modified Centerline and Hybrid Tailings Dams

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. A21; 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. A21). 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. A2a with Fig. A21). 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 downstream" method. In fact, ICOLD (2021) essentially repeats the diagram from Haile and Brouwer (1994) (see Fig. A21), but labels it the “modified upstream” method (see Fig. A22). 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., 2020). 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.” However, none of the four Latin American countries (Brazil, Chile, Ecuador, Peru) that prohibit upstream dams have explicitly confirmed that the same prohibition includes modified centerline dams. In fact, I have not been able to find even any proposals to construct modified centerline dams in the countries that prohibit upstream dams.

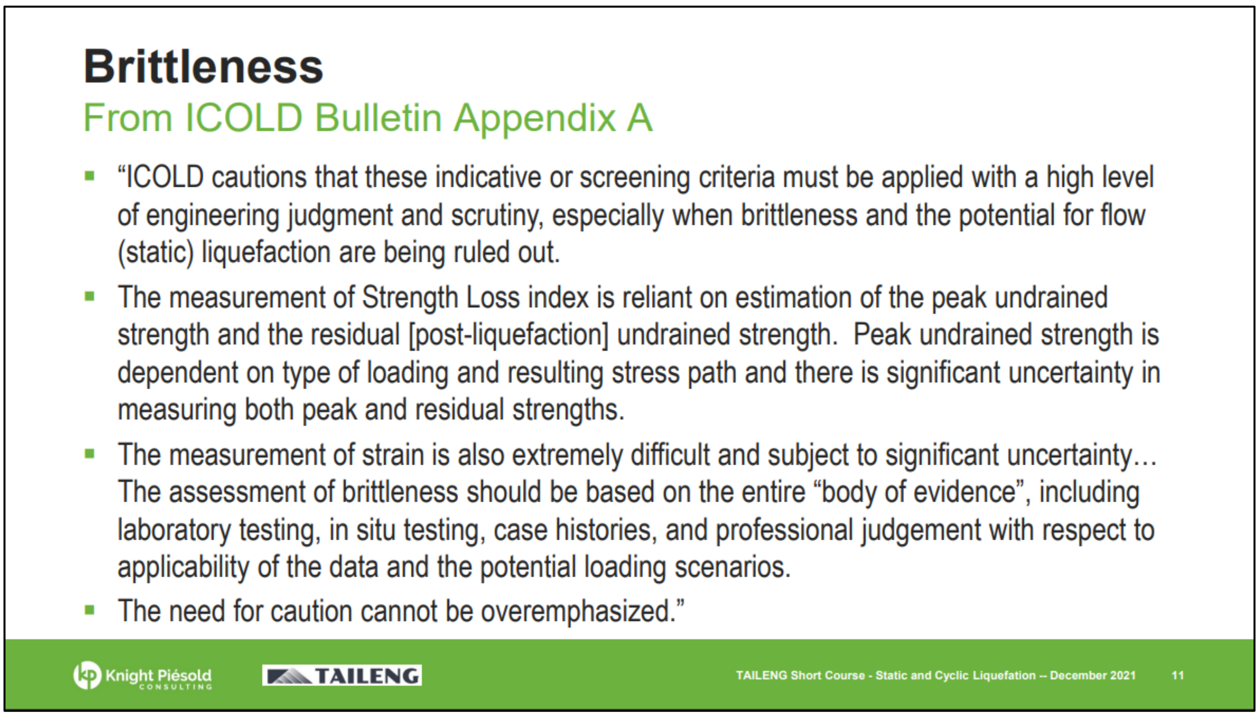

Figure A19. The upcoming ICOLD bulletin points out that it is difficult to accurately measure both the peak (yield) strength and the residual (liquefied or post-liquefaction) strength, so that there is considerable uncertainty in the strength loss index. According to the bulletin, “ICOLD cautions that these indicative or screening criteria must be applied with a high level of engineering judgment and scrutiny, especially when brittleness and the potential for flow (static) liquefaction are being ruled out” (Ridlen, 2021). The upcoming ICOLD bulletin is essentially saying that brittle behavior should be assumed as a default, unless there is substantial evidence to the contrary. Slide from Ridlen (2021).

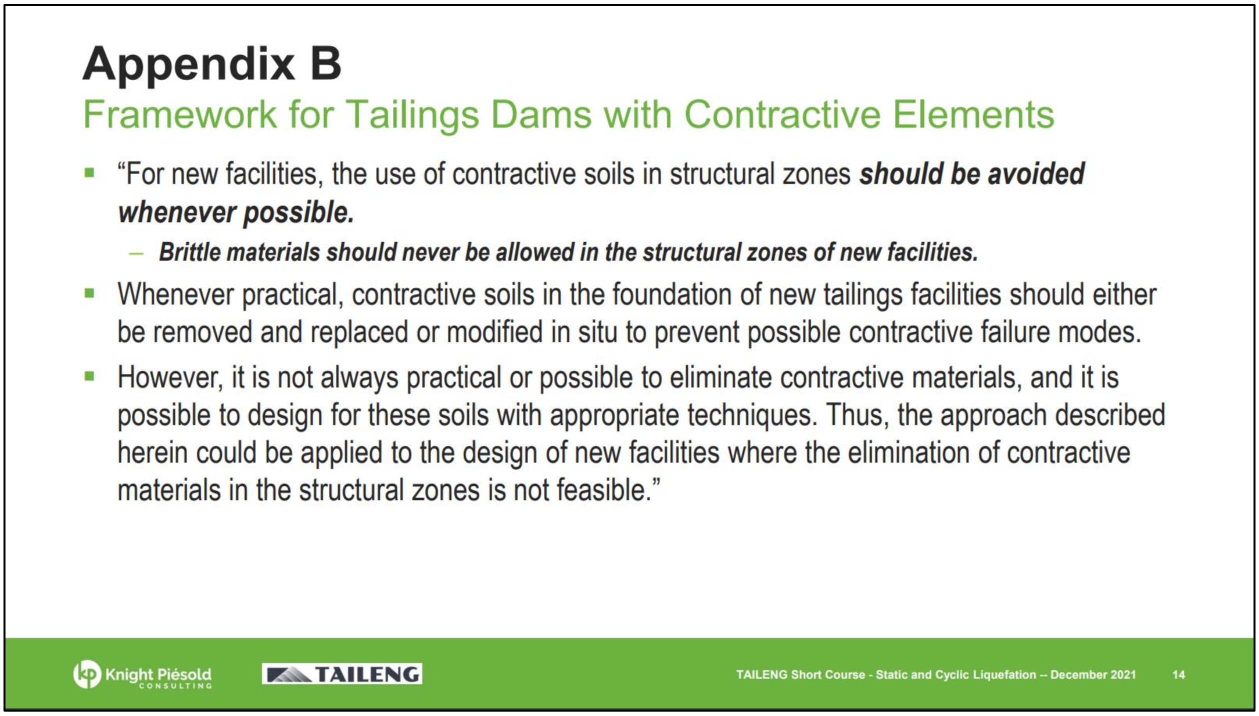

Figure A20. For the evaluation of the impact of the post-Brumadinho guidance on the use of the upstream construction method for tailings dams, the most important sentence from the upcoming ICOLD bulletin is "**Brittle materials should never be allowed in the structural zones of new facilities**" (Ridlen, 2021). According to another post-Brumadinho ICOLD bulletin (ICOLD, 2021), the structural zone of an upstream dam includes the stack of beaches or all tailings that are underneath the dikes (see Fig. A8). The combination of the two ICOLD bulletins implies that the impoundment of brittle tailings by an upstream dam is possible only if it can be guaranteed that the tailings beneath the dikes will be unsaturated and compacted into a dilative state (so that expansion, rather than further compaction will occur after disturbance) by the overlying beaches and dikes. Slide from Ridlen (2021).

It is important to note that "modified centerline" refers only to an upstream-sloping contact between the successive dikes and the underlying, uncompacted tailings and does not refer to any other modification of the centerline method. For example, the permit for the tailings dam that failed at the Mount Polley mine in British Columbia in 2014 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. A23a-b). According to Independent Expert Engineering Investigation and Review Panel (2015b), "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 (2015b), "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."

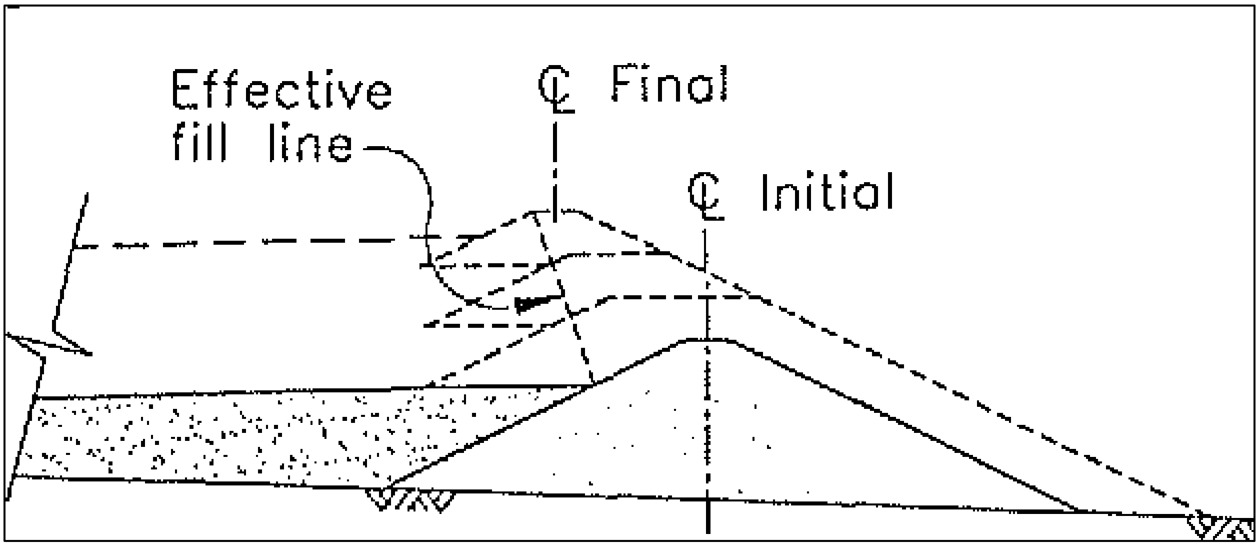

Figure A21. In the modified centerline construction method, the contact between the successive dikes and the uncompacted tailings slopes in an upstream direction (compare with Figs. A2a and A2c). According to TailPro Consulting (2022), "In countries where upstream construction is not permitted (i.e. 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" (Morrill et al., 2020). Figure from Haile and Brouwer (1994).

The tailings dam failure database in Center for Science in Public Participation (2022) refers to the dam type of the tailings dam at the Mount Polley mine as "Modified CL [Centerline])." (This database is discussed in detail in the section on History of Tailings Dam Databases.) However, this use of the phrase "modified centerline" should be regarded as non-standard terminology (compare Figs. A21-22 with Figs. A23a-b). Once the Stage 2 raise had been constructed, the entire tailings dam should be regarded as an upstream dam, since it retained the essential feature that the dam was constructed on top of uncompacted tailings, which could not be altered by any future dam raises (see Figs. A23a-b).

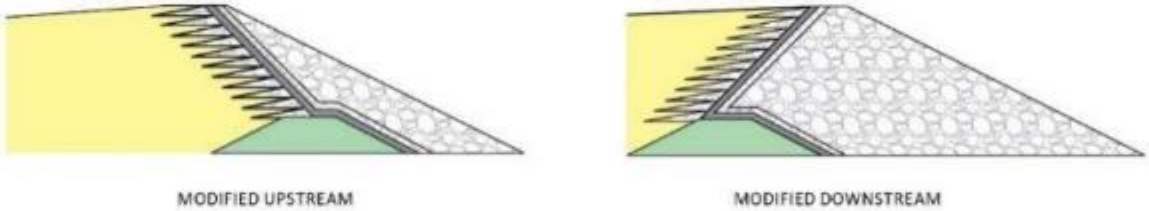

Fig. 4.3
Geometry of modified upstream and modified downstream centerline dams

Figure A22. The above diagram from ICOLD (2021) confirms that what has been called the "modified centerline" method (see Fig. A21) 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. A2a). 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. According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam still constitutes an upstream dam" (Morrill et al., 2020). As a related example, at the Cobre and Aguzadera tailings dams at the Riotinto mine in Spain, rock walls were constructed in the downstream direction on top of existing upstream dams (see Fig. A23; Emerman, 2019). At these dams, the gossan sands that compose the dam were also never compacted (Emerman, 2019). Although dams constructed by the downstream method are, in general, less vulnerable to failure, under these circumstances, the rock wall actually increases the probability of liquefaction by increasing the load on both the underlying dam and the underlying tailings.

Effect of Height on Risk of Failure of Tailings Dams

The effect of height on the risk of tailings dam failure is more complex than the effect of construction method. Since the gravitational stress on a dam increases with height, the likelihood of failure should increase as dams are raised if no other steps are taken to ensure dam safety. (For example, raising a dam could be accompanied by constructing a buttress at the toe of a dam or by increasing the number of monitoring instruments.) Therefore, in evaluating the effect of a planned increase in dam height, the important consideration is the other steps that will accompany the planned height increase. This point was illustrated by Franks et al. (2021) who found a steadily increasing incidence of stability issues as tailings dam heights were increased from 0-100 meters with a change in the pattern for dams taller than 100 meters (see Fig. A25). According to Franks et al. (2021), "The likelihood of a stability issue being reported for a facility with an embankment between 80-100m is notably 5 times higher than for facilities with embankments between 0-20m. But in the relatively small number of cases where an embankment height exceeds 100m, there is a decline in the proportion of facilities that reported a stability issue. A possible explanation for this, may be that higher standards of construction have been applied for facilities with very high embankments (although we have no direct measure of this)" (see Fig. A25).

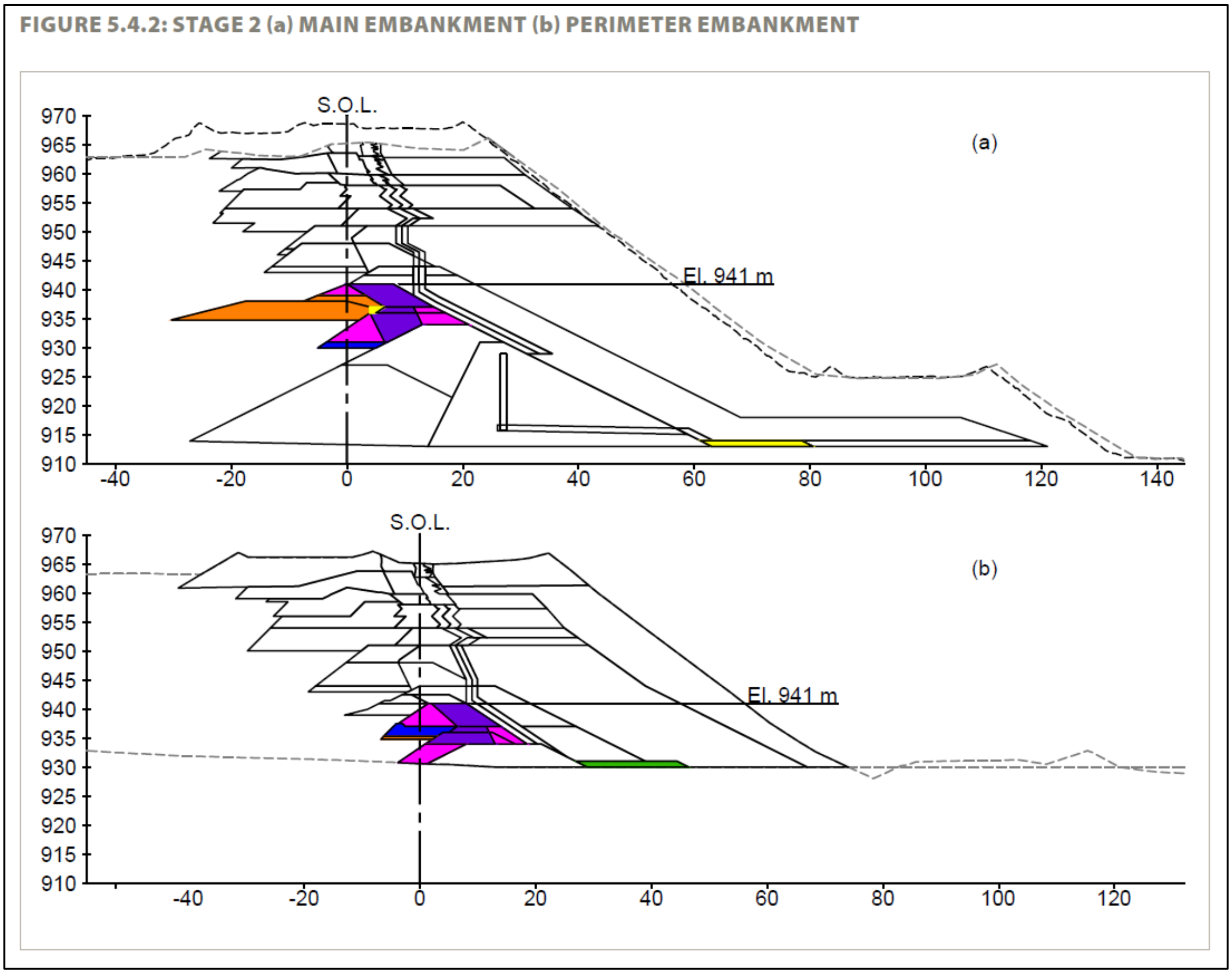

Figure A23a. Although the tailings dam at the Mount Polley mine was designed and permitted as a centerline dam, the Stage 2 dam raise (shown in colors) was constructed using the upstream method. According to Independent Expert Engineering Investigation and Review Panel (2015b), "The as-built configuration 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. A2a, A2c and A21). According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam still constitutes an upstream dam" (Morrill et al., 2020). Figure from Independent Expert Engineering Investigation and Review Panel (2015b).

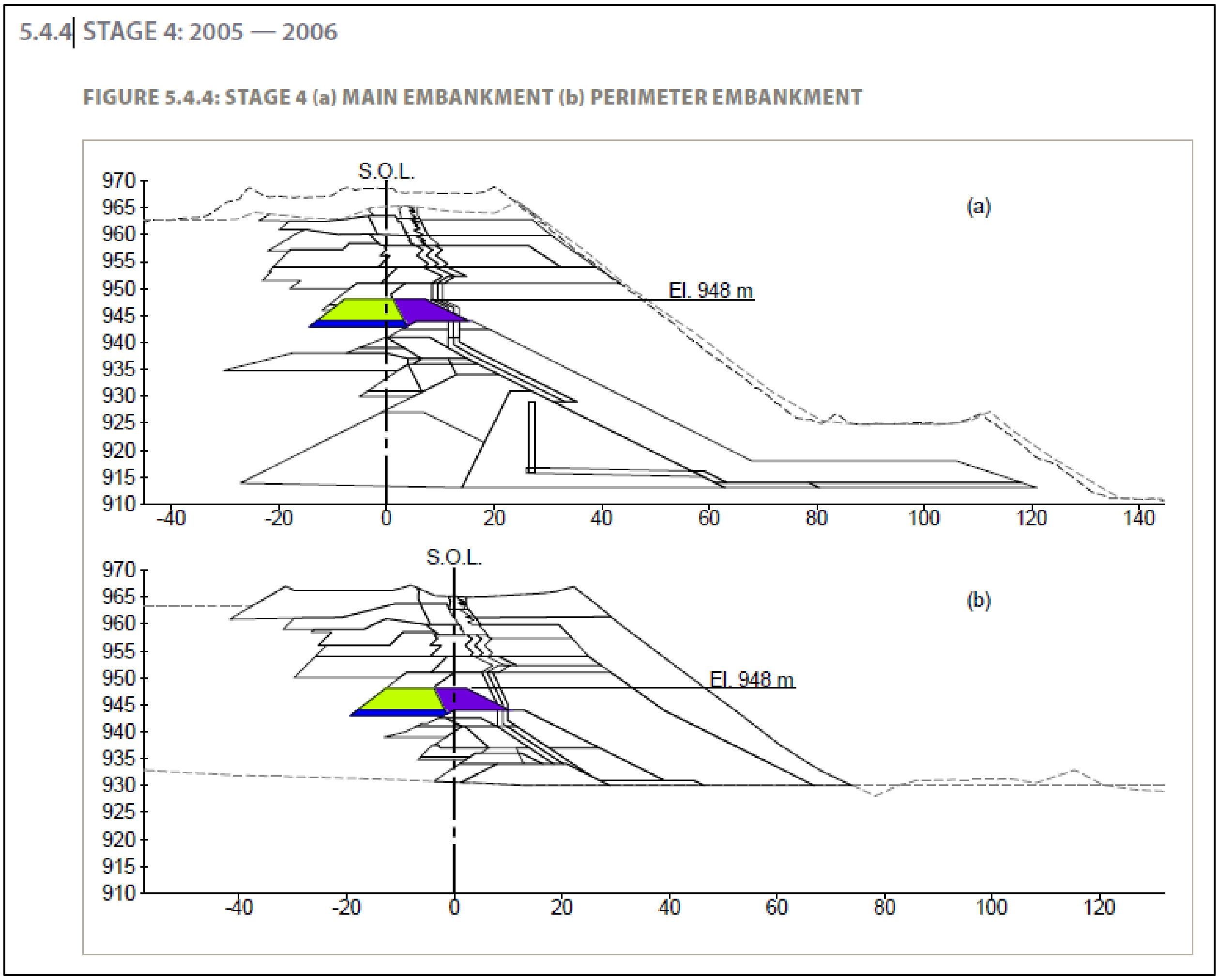

Figure A23b. Although the tailings dam at the Mount Polley mine was designed and permitted as a centerline dam, the Stage 4 dam raise (shown in colors) was constructed using the upstream method. According to Independent Expert Engineering Investigation and Review Panel (2015b), "As illustrated in Figure 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. A2a, A2c and A21). According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam still constitutes an upstream dam" (Morrill et al., 2020). Figure from Independent Expert Engineering Investigation and Review Panel (2015b).

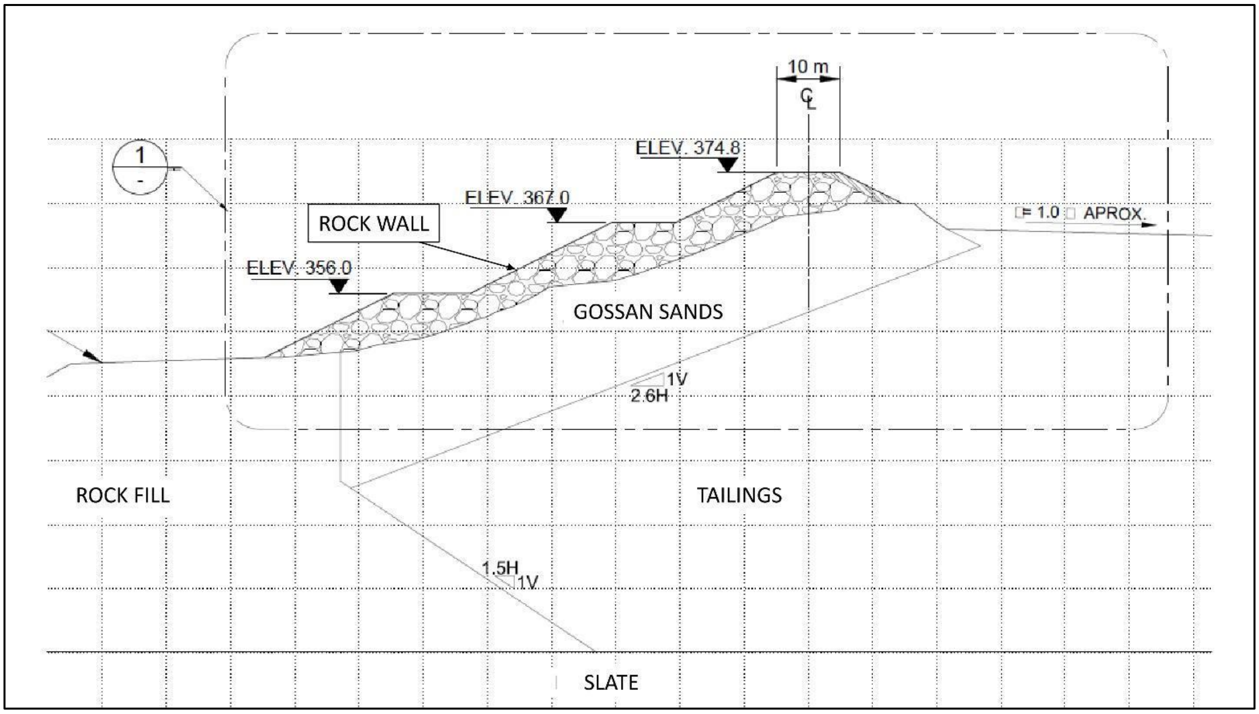

Figure A24. The Aguzadera dam at the Riotinto mine was constructed using the upstream method (compare with Fig. A2a). Although the subsequent rock wall was constructed in the downstream direction (compare with Fig. A2c), it does not change the essential feature that the uncompacted tailings are beneath the dam (labeled as gossan sands). In fact, the gossan sands that compose the dam were also never compacted (Emerman, 2019). The rock wall actually increases the probability of liquefaction by increasing the load on both the underlying dam and the underlying tailings. According to Safety First: Guidelines for Responsible Mine Tailings Management, "A downstream or centerline raise constructed on top of an existing upstream dam still constitutes an upstream dam" (Morrill et al., 2020). Dashed squares are 10 meters on a side. Figure from Emerman (2019).

The same pattern is seen when comparing the heights of failed tailings dams in the USA (Center for Science in Public Participation, 2022) with the heights of all tailings dams in the National Inventory of Dams (USACE, 2022). In this case, the more complete database of the National Inventory of Dams (USACE, 2022) is used, since it includes dam heights (although not methods of construction). When all dam heights are considered, the difference between the mean height of an existing tailings dam (78.2 feet) and the mean height of a failed tailings dam (79.0 feet) is not statistically significant ($P = 0.94$) (see Fig. 26a). (The P-value is the probability that the difference between the means of two populations is statistically significant. In this report, all P-values for comparisons between two means were calculated using the t-test for unpaired samples and unequal variance.) However, a height of 140 feet emerges as a key cut-off for tailings dam safety in the USA (see Fig. 26a). When only heights less than or equal to 140 feet are considered, the difference between the mean height of tailings dams (42.6 feet) and the mean height of failed tailings dams (52.8 feet) is statistically significant at better than the 95% confidence level ($P = 0.02$) (see Fig. 26a). On the other hand, when only heights greater than 140 feet are considered, the difference between the mean height of tailings dams (303.1 feet) and the mean height of failed tailings dams (203.4 feet) is statistically significant at better than the 99% confidence level ($P = 0.005$) (see Fig. 26a). In other words, in the USA, for tailings dams with heights less than 140 feet, shorter tailings dams have been safer than taller tailings dams, probably simply because there is greater gravitational stress on taller tailings dams. For tailings dams with heights greater than 140 feet, taller tailings dams have been safer than shorter tailings dams. Although there is still greater gravitational stress on taller tailings dams, the likely conclusion is that stricter safety standards have been applied to tailings dams taller than 140 feet, although there is no direct measure of this, as also stated by Franks et al. (2021).

The same pattern is not seen when comparing the heights of failed tailings dams globally (Center for Science in Public Participation, 2022), including in the USA, with the heights of all tailings dams in the Global Tailings Portal (GRID-Arendal, 2022). In this case, the difference between the mean height at failure (33.2 meters) and the mean height of a failed tailings dam (27.7 meters) is statistically significant at better than the 99% confidence level ($P = 0.003$) (see Fig. 26b). In other words, on a global basis, taller tailings dams have been safer than shorter tailings dams across the spectrum of dam heights, which is different from the conclusion reached by Franks et al. (2021), who were considering stability issues, as opposed to failures. It is interesting that the statistical significance is lost ($P = 0.18$) when the tailings dams are restricted to upstream dams, still on a global basis, including the USA (see Fig. 27a). In other words, on a global basis, although taller tailings dams have been safer than shorter tailings dams, taller upstream tailings dams have been no safer than shorter upstream tailings dams. However, when upstream tailings dams are restricted to the USA, the difference between the mean height of existing upstream tailings dams (139.2 feet) and failed upstream tailings dams (90.3 feet) is highly statistically significant at better than the 99.9% confidence level ($P = 0.0008$) (see Fig. 27b). In other words, based on the available data, taller upstream tailings dams in the USA are much less likely to fail than shorter upstream tailings dams in the USA. It should be noted that, by the time that the database has been restricted to upstream tailings dams in the USA, the database has become very small (29 failed tailings dams and 118 existing tailings dams).

At this point, it is important to emphasize that simply increasing the height cannot cause dams to be safer. From a purely physical standpoint, a taller dam has a higher likelihood of failure simply due to the greater gravitational stress. Taller tailings dams can be safer only if the increase in safety standards is disproportionate to the increase in height. This appears to have been an historical trend under certain circumstances, but it is not guaranteed. The obvious question to ask regarding any proposed increase in dam height is: In what way will safety standards increase disproportionately to the increase in height?

On the other hand, there is another pattern that, when tailings dams do fail, the consequences are greater for taller than for shorter tailings dams. On a global basis, including the USA, the mean heights of tailings dams have been 39.9 meters, 31.9 meters, and 22.3 meters for Very Serious, Serious and Other tailings dam failures, respectively (see Fig. 28a). According to the ANOVA (Analysis of Variance) test, the differences among the three mean heights are highly statistically significant at better than the 99.9% confidence level ($P = 0.0002$) (see Fig. 28a). For tailings dams restricted to the USA, the mean heights of tailings dams have been 103.8 feet, 111.8 feet, and 67.5 feet, for Very Serious, Serious and Other tailings dam failures, respectively (see Fig. 28b). According to the ANOVA test, the differences among the three mean heights are not statistically significant ($P = 0.167$) (see Fig. 28b). However, if a comparison is made between the mean height of tailings dams that underwent Very Serious + Serious failures (109.8 feet) and Other failures (67.5 feet), the difference becomes statistically significant at better than the 95% confidence level ($P = 0.047$) (see Fig. 28b). The use of the ANOVA and t-tests did not include Waste-Related Accidents since they are a fundamentally different kind of failure.

Fig. S7. Relationship between facility embankment height and reported occurrence of stability issues, all facilities. Top: distribution of tailings facilities by embankment height. Bottom: proportion of facilities reporting a stability issue by embankment height. *Note*: shading indicates number of facilities reporting a stability issue; there are no instances of stability issues in heights above 140m; vertical error bars for these categories show the range of fractions for which the probability of finding zero in a sample of that size is greater than 74% (the same confidence interval as shown for the other points).

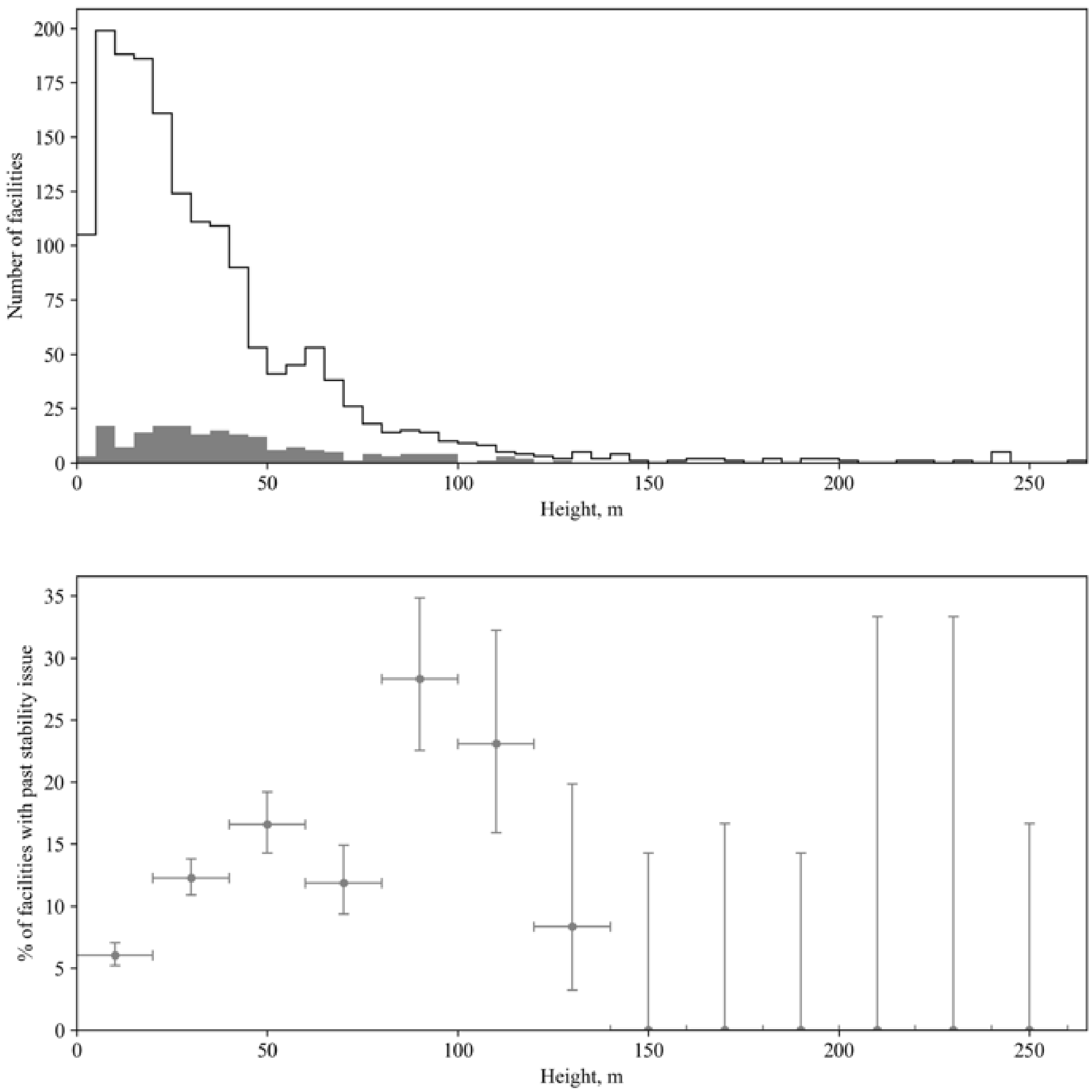

Figure A25. According to Franks et al. (2021), “The likelihood of a stability issue being reported for a facility with an embankment between 80-100m is notably 5 times higher than for facilities with embankments between 0-20m. But in the relatively small number of cases where an embankment height exceeds 100m, there is a decline in the proportion of facilities that reported a stability issue. A possible explanation for this, may be that higher standards of construction have been applied for facilities with very high embankments (although we have no direct measure of this).” Figure from Franks et al. (2021).

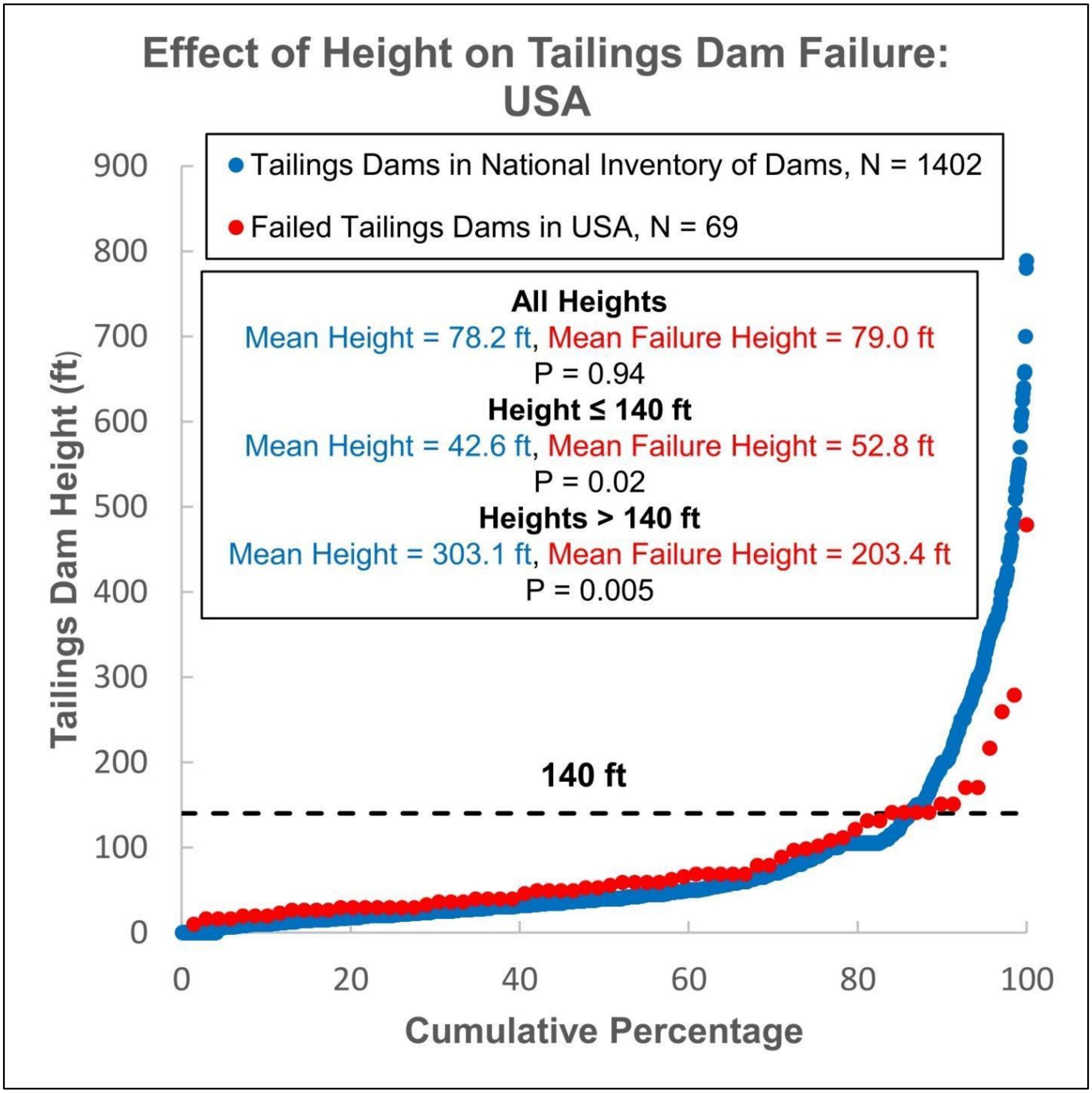

Figure A26a. When all heights are considered for tailings dams in the USA, the difference between the mean height of tailings dams (78.2 feet) and the mean height of failed tailings dams (79.0 feet) is not statistically significant (P = 0.94). However, when only heights less than or equal to 140 feet are considered, the difference between the mean height of tailings dams (42.6 feet) and the mean height of failed tailings dams (52.8 feet) is statistically significant at better than the 95% confidence level (P = 0.02). On the other hand, when only heights greater than 140 feet are considered, the difference between the mean height of tailings dams (303.1 feet) and the mean height of failed tailings dams (203.4 feet) is statistically significant at better than the 99% confidence level (P = 0.005). In other words, in the USA, for tailings dams with heights less than 140 feet, shorter tailings dams have been safer than taller tailings dams, probably simply because there is greater gravitational stress on taller tailings dams. For tailings dams with heights greater than 140 feet, taller tailings dams have been safer than shorter tailings dams. Although there is still greater gravitational stress on taller tailings dams, the likely conclusion is that stricter safety standards have been applied to tailings dams taller than 140 feet, although there is no direct measure of this. Tailings dam heights from USACE (2022) and heights of failed tailings dams from Center for Science in Public Participation (2022).

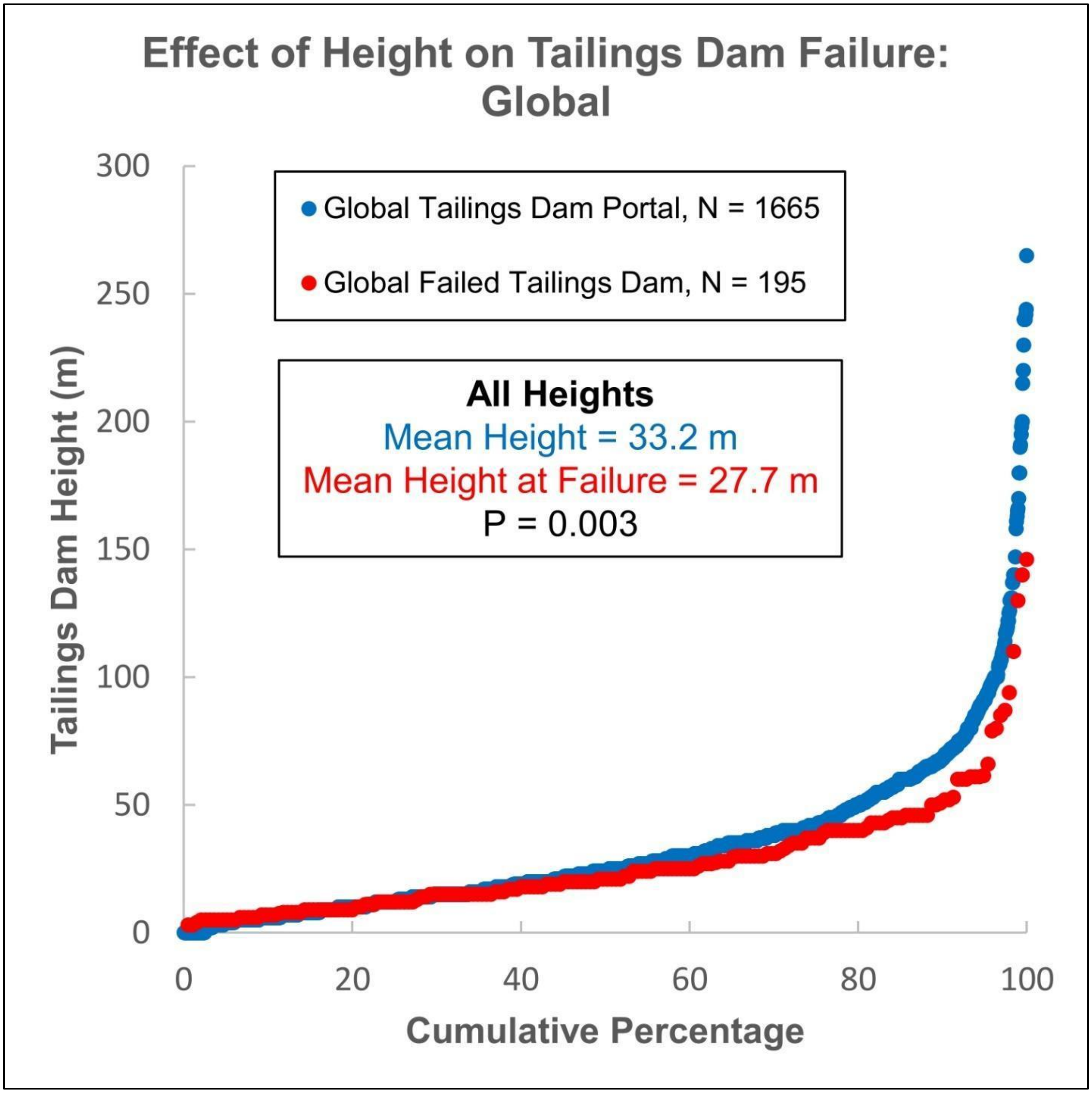

Figure A26b. When all heights are considered for global tailings dams (including tailings dams in the USA), the difference between the mean height of tailings dams (33.2 meters) and the mean height of failed tailings dams (27.7 meters) is statistically significant at better than the 99% confidence level ($P = 0.003$). In other words, on a global basis, taller tailings dams have been safer than shorter tailings dams across the spectrum of dam heights, which is different from the conclusion reached by Franks et al. (2021), who were considering stability issues, as opposed to failures. Although there is greater gravitational stress on taller tailings dams, the likely conclusion is that stricter safety standards have been applied to taller tailings dams, although there is no direct measure of this. Tailings dam heights from GRID-Arendal (2022) and heights of failed tailings dams from Center for Science in Public Participation (2022).

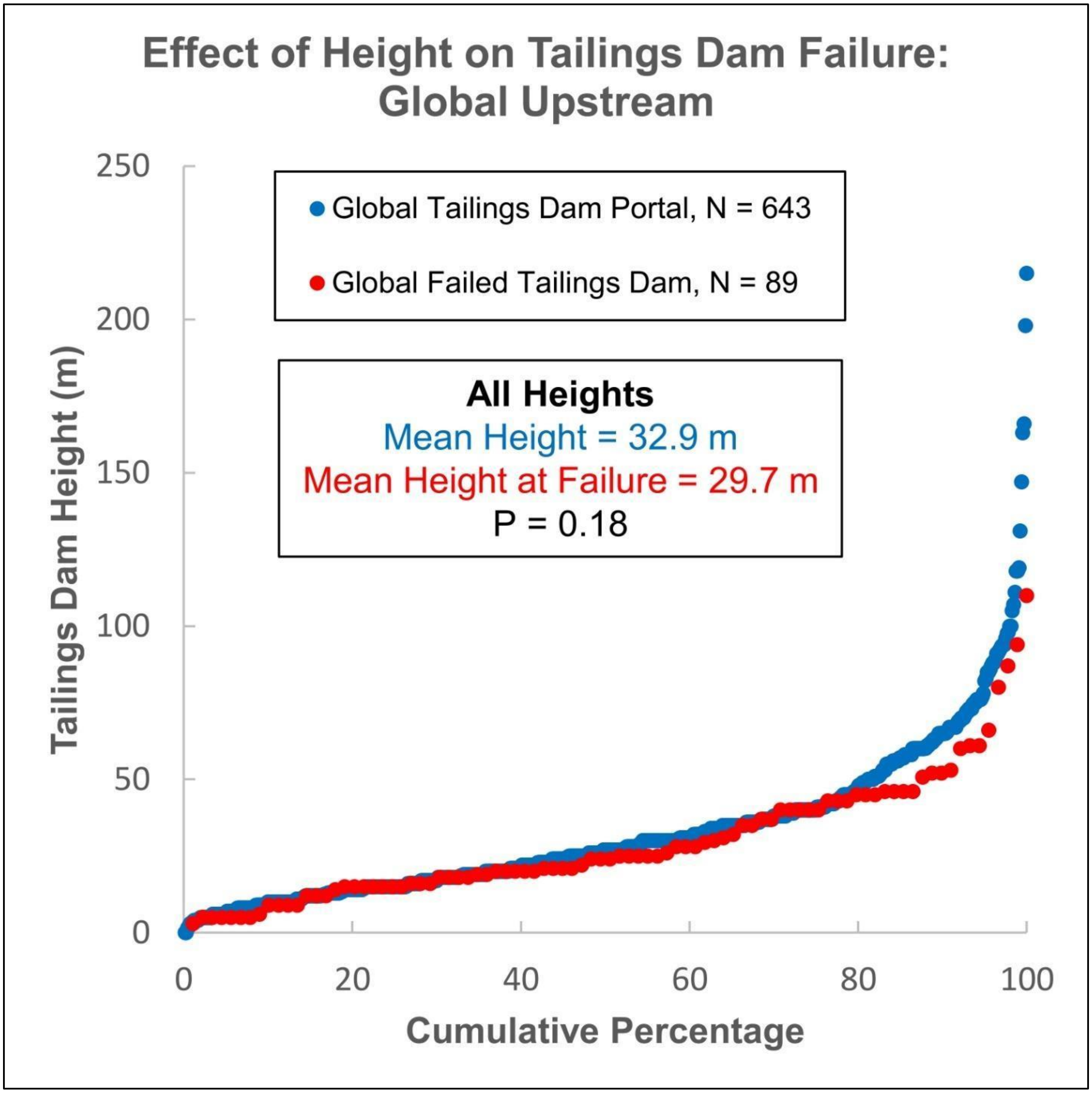

Figure A27a. When all heights are considered for global upstream tailings dams (including upstream tailings dams in the USA), the difference between the mean height of tailings dams (32.9 meters) and the mean height of failed tailings dams (29.7 meters) is not statistically significant ($P = 0.18$). In other words, on a global basis, although taller tailings dams have been safer than shorter tailings dams (see Fig. A26b), taller upstream tailings dams have been no safer than shorter upstream tailings dams. Tailings dam heights from GRID-Arendal (2022) and heights of failed tailings dams from Center for Science in Public Participation (2022).

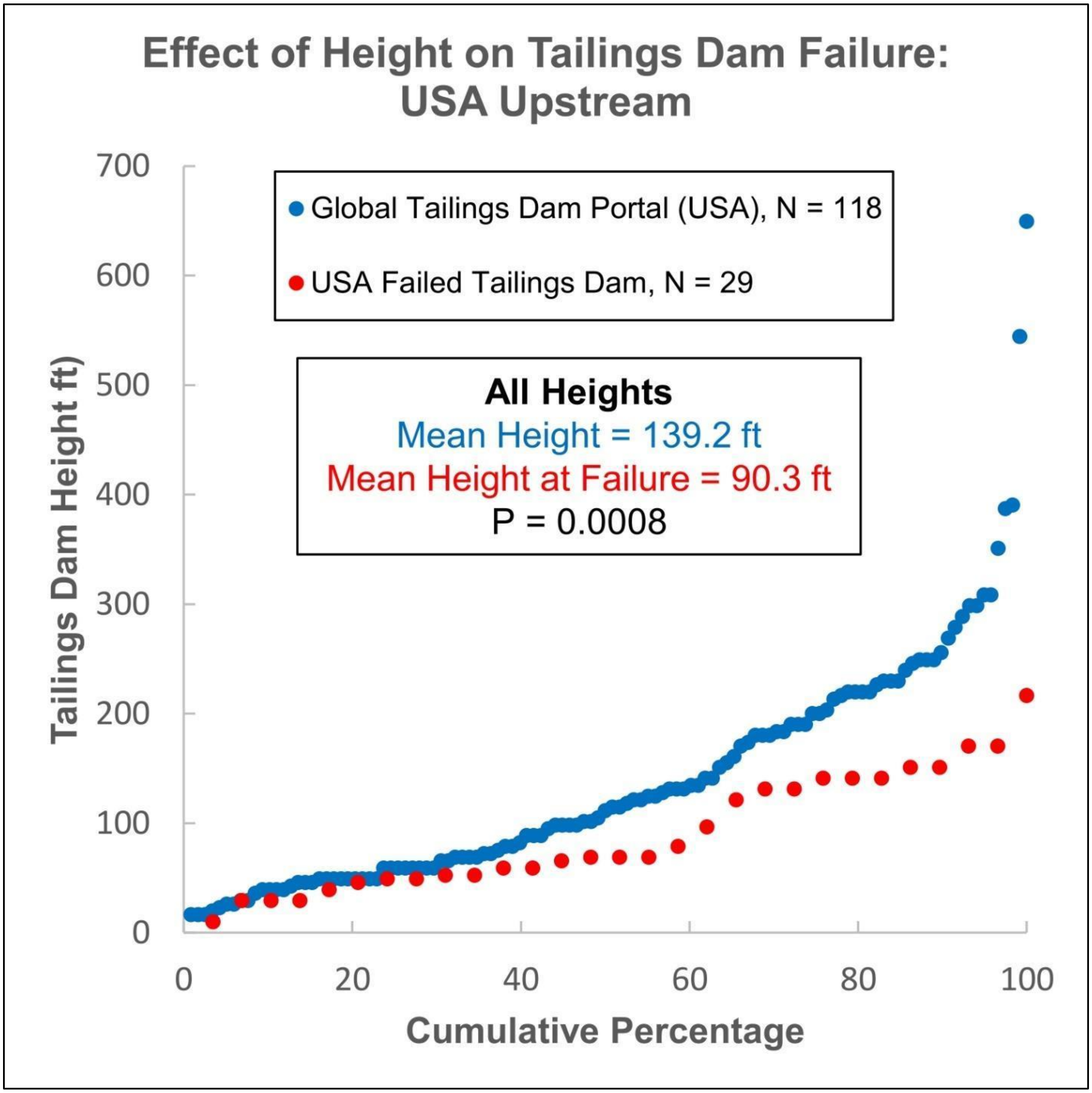

Figure A27b. When all heights are considered for upstream tailings dams in the USA, the difference between the mean height of tailings dams (139.2 feet) and the mean height of failed tailings dams (90.3 feet) is statistically significant at better than the 99.9% confidence level ($P = 0.0008$). In other words, for the USA, taller upstream tailings dams have been safer than shorter upstream tailings dams. Although there is greater gravitational stress on taller upstream tailings dams, the likely conclusion is that stricter safety standards have been applied to taller upstream tailings dams, although there is no direct measure of this. Tailings dam heights from GRID-Arendal (2022) and heights of failed tailings dams from Center for Science in Public Participation (2022).

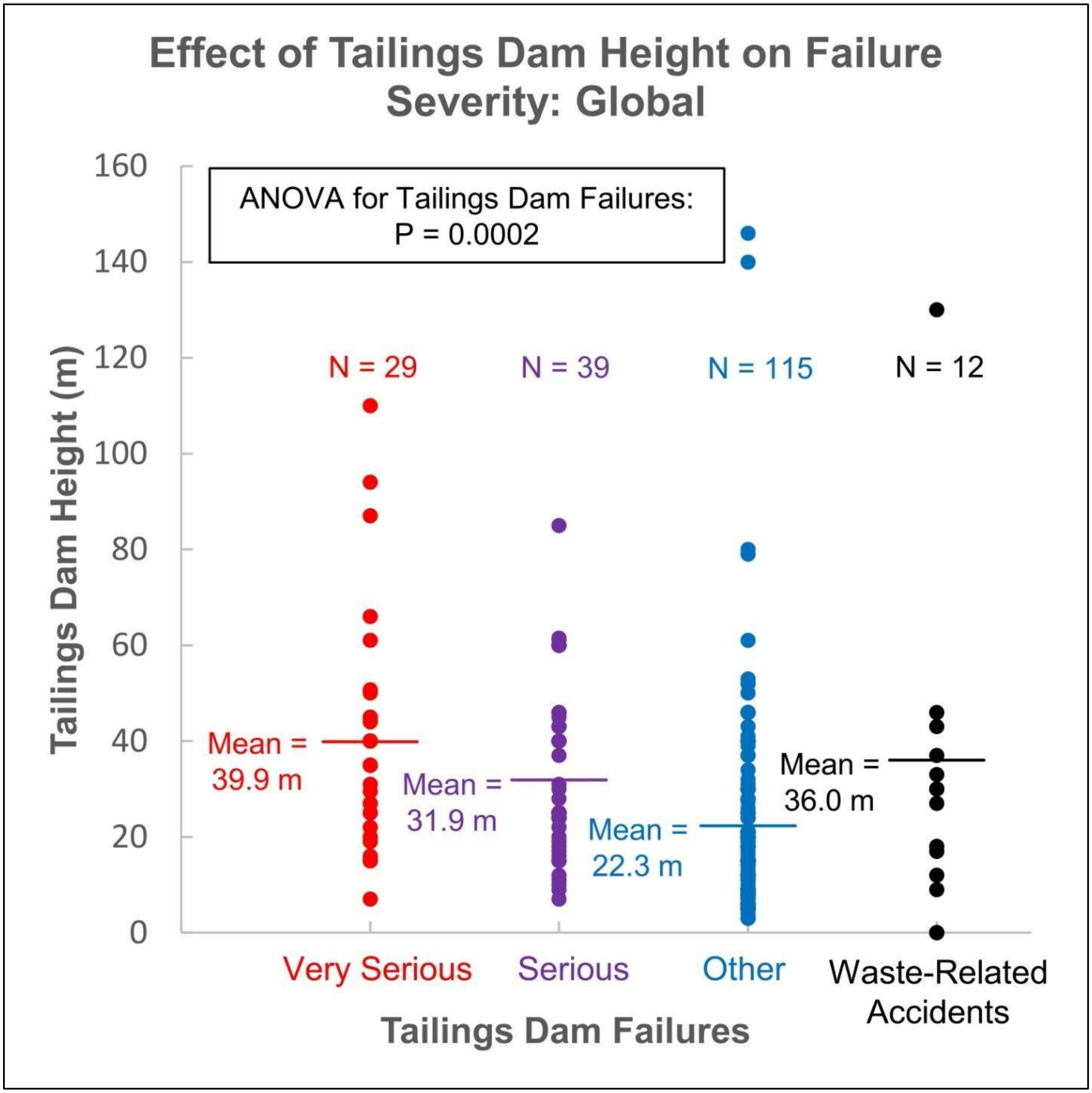

Figure A28a. For global failed tailings dams (including failed tailings dams in the USA), the differences among the mean heights of dams that underwent Very Serious (39.9 meters), Serious (31.9 meters feet) and Other (22.3 meters) Tailings Dam Failures are statistically significant at better than the 99.9% confidence level ($P = 0.0002$). Waste-related Accidents were not included in calculations of P-values. Data and severity codes from Center for Science in Public Participation (2022):

Very Serious Tailings Dam Failure = multiple loss of life and/or release of ≥ 1,000,000 m^3 tailings and/or tailings travel of 20 km or more;

Serious Tailings Dam Failure = loss of life and/or release of ≥ 100,000 m^3 tailings;

Other Tailings Dam Failure = engineering/facility failure other than those classified as Very Serious or Serious, no loss of life;

Waste-Related Accident = related facility tailings failures (e.g. sinkholes, pipelines), and non-tailings incidents (e.g. mine plug failures, waste rock failures, etc.).

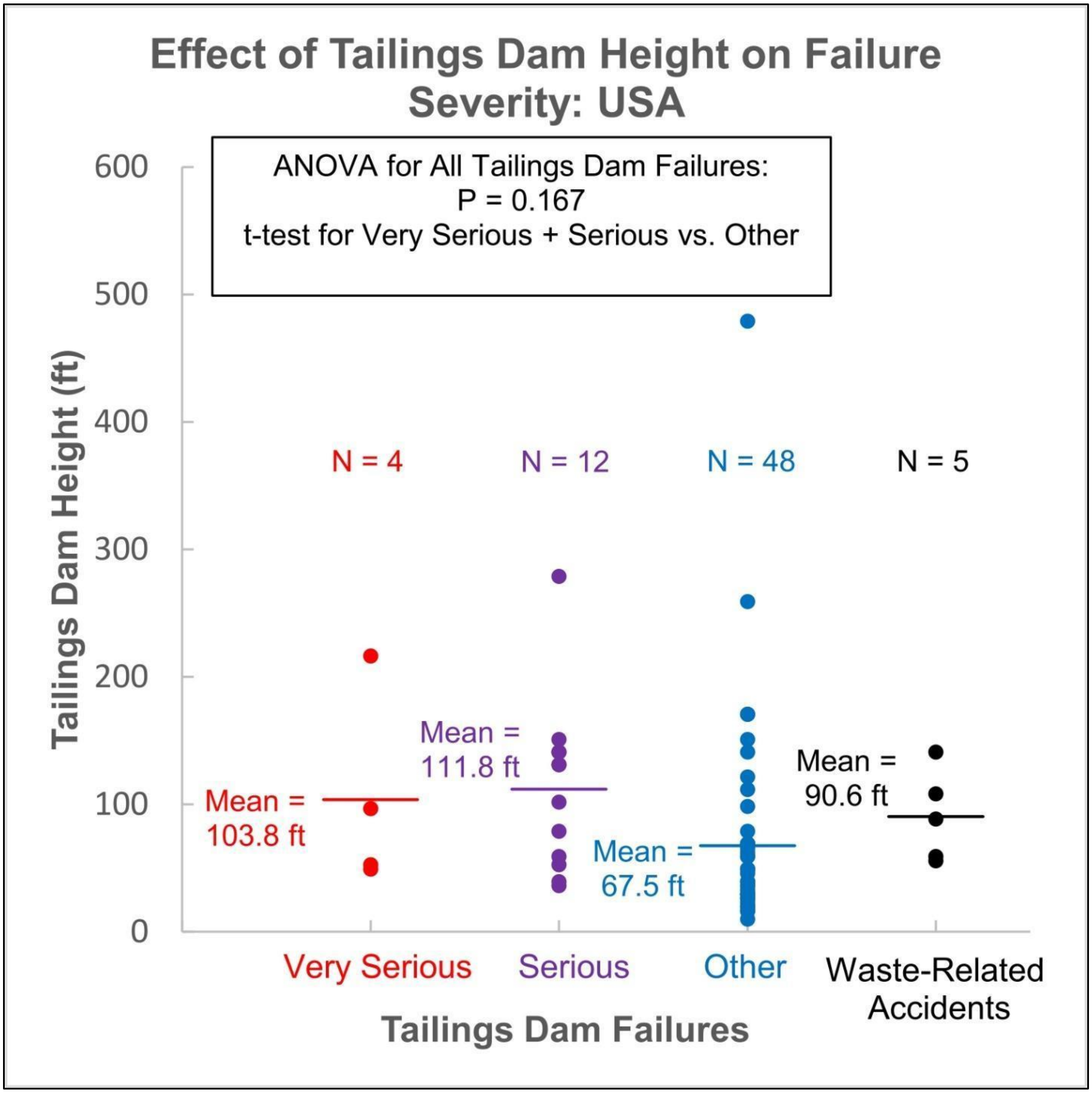

Figure A28b. For failed tailings dams in the USA, the differences among the mean heights of dams that underwent Very Serious (103.8 feet), Serious (111.8 feet) and Other (67.5 feet) Tailings Dam Failures are not statistically significant ($P = 0.167$). However, the difference between the mean heights of dams that underwent Very Serious + Serious (109.8 feet) and Other (67.5 feet) failures is statistically significant at better than the 95% confidence level ($P = 0.047$). Waste-related Accidents were not included in calculations of P-values. Data and severity codes from Center for Science in Public Participation (2022):

Very Serious Tailings Dam Failure = multiple loss of life and/or release of ≥ 1,000,000 m^3 tailings and/or tailings travel of 20 km or more;

Serious Tailings Dam Failure = loss of life and/or release of ≥ 100,000 m^3 tailings;

Other Tailings Dam Failure = engineering/facility failure other than those classified as Very Serious or Serious, no loss of life;

Waste-Related Accident = related facility tailings failures (e.g. sinkholes, pipelines), and non-tailings incidents (e.g. mine plug failures, waste rock failures, etc.).