Determination of the Raise Categories for Sparsely-Documented Tailings Dams in British Columbia, Canada

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LIGHTNING SUMMARY

Out of 19 mine sites with tailings dams with unknown raise categories under consideration for a new tailings storage database for British Columbia, it was determined that two included centerline dams, one included hybrid (mixed centerline-downstream) dams, one included downstream dams, one included a filtered-tailings stack, seven included single-stage dams, none included upstream dams, one was Other, and six remained unknown. The determinations were based upon explicit references, cross-sections, dam heights, and construction materials.

EXECUTIVE SUMMARY

The development of a new tailings storage database for British Columbia resulted in 19 mine sites for which the raise categories were unknown. Unlike conventional water-retention dams, tailings dams are typically raised in stages as more tailings are generated that require impoundment and as more mine waste becomes available for dam construction. The most common raise categories are upstream, downstream and centerline. In the upstream and downstream methods, successive dikes are built in the upstream and downstream directions, respectively. In the centerline method, successive dikes are constructed by placing construction material on the tailings beach and on the slope downstream of the previous dike, so that the central lines of the raises coincide as the dam is built upwards. Alternative raise categories are hybrid dams (in which the raises can be a mix of centerline, downstream and upstream), single-stage dams, and filtered-tailings stacks (in which the tailings are filtered to the consistency of a moist soil prior to storage). The significance of the raise categories is that upstream dams have both the lowest construction costs and the greatest vulnerability to failure.

Careful reading of the available documentation showed that six mine sites included explicit, although obscure, references to the correct raise categories. Four of the mine sites (with one overlap with the previous six) included cross-sections from which the raise categories could be determined. The use of the Global Tailings Portal showed that the mean dam heights for centerline, downstream, filtered-stack, hybrid, single-stage and upstream dams are 43.1 meters, 35.8 meters, 40.6 meters, 49.3 meters, 15.7 meters, and 32.9 meters, respectively. Thus, in the absence of other information, single-stage dams can typically be distinguished by their shorter heights. In addition, in the absence of other information, single-stage dams can typically be distinguished by the use of natural rockfill or earthfill for construction material, since they are often constructed before tailings or other mine waste are available.

The conclusions can be summarized as follows:

1) The Huckleberry and Mineral King sites include centerline dams.
2) The Quinsam – North Pit site includes hybrid (mixed centerline – downstream) dams.

3) The QR Mine TSF site includes downstream dams.
4) The Silvertip site includes a filtered tailings stack.
5) The Coxey/Red Mountain/Rossland, Gallowai/Bull River, Goldstream (Revelstoke), HVC - 7Day Pond, May Mac (Bow/Boundary Falls), Valentine Mountain/Ashlu, and Yellowjacket sites include single-stage dams.
6) In terms of raise categories, the Candorado/Hedley site is classified as Other, since the tailings are simply heaped with no dewatering or impoundment.
7) The raise categories are unknown at the Dome Mountain, Lawyers/Cheni, Mount Copeland, New Privateer/Privateer/Zeballos, Northair, and Taurus Gold sites.
8) None of the mine sites include upstream dams. However, the QR Mine TSF site retains some of the vulnerability to failure of upstream dams since some dam construction material has been placed on top of existing tailings or waste rock.

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OVERVIEW

Mine tailings are the wet and crushed rock particles that remain after the commodity of value has been removed. Typically, these mine tailings are impounded by a tailings dam and permanently stored aboveground. A database of tailings storage is British Columbia is currently under development. For 19 mining sites (sometimes including multiple tailings dams), the raise category is still unknown (see Table 1). Unlike conventional water-retention dams, which are constructed entirely before the reservoirs are filled with water, tailings dams are normally constructed in stages as more tailings are generated that require storage. For the tailings dam database, the significance of the raise category is that some raise categories, especially the upstream method, are far more vulnerable to failure than others.

Table 1. Raise categories for sparsely-documented tailings dams, British Columbia

Site Name	Dam Name	Max Height (m)	Construction Materials
Sites with Centerline Dams			
Huckleberry[1]	TMF-2 Main Dam	90	Rockfill, glacial till
	TMF-2 Orica Saddle Dam[2]	10	Rockfill, glacial till
	East Pit Plug Dam	—	Rockfill, earthfill, waste rock
	TMF-3 Main Dam[3]	—	Rockfill, earthfill, waste rock
	TMF-3 Saddle Dam[3]	—	Rockfill, earthfill, waste rock
Mineral King[4,5]		6	Coarse tailings
Sites with Hybrid (Centerline-Downstream) Dams			
Quinsam - North Pit[6]	North Embankment	50	Coarse coal rejects, cast blast
	South Embankment[7]	45	Coarse coal rejects, cast blast
	East Embankment[8]	15-20	Coarse coal rejects, glacial till
	West Embankment[8]	50	Coarse coal rejects, glacial till
Sites with Downstream Dams			
QR Mine TSF[9]	Cross Dyke	—	Rockfill, glacial till
	Tailings Dam	—	Rockfill, glacial till, waste rock
Sites with Filtered Tailings Stacks			
Silvertip[10]		—	Waste rock
Sites with Single-Stage Dams			
Coxey/Red Mountain/Rossland[11]	Good Friday TSF	20	Glacial till, rockfill
	Jumbo TSF	28	Rockfill
Gallowai/Bull River[12]		30	Glacial till
Goldstream (Revelstoke)[13]	West Dam	23	Earthfill
	North Dam	16	Earthfill
HVC - 7Day Pond[14]		6	—
May Mac (Bow/Boundary Falls)[16]		12-15	Earthfill
Valentine Mountain/Ashlu[16]		9	—
Yellowjacket[17]	TSF1	4	Gravel, cobbles
	TSF2	4	Gravel, cobbles

	TSF3	4.5	Glacial till, gravel
Sites with Other Raise Categories			
Candorado/Hedley[18,19]		—	—
Sites with Unknown Raise Categories			
Dome Mountain[20,21]		—	—
Lawyers/Cheni		—	—
Mount Copeland		—	—
New Privateer/Privateer/Zeballos		—	—
Northair		—	—
Taurus Gold		—	—

[1]Golder Associates Ltd. (2021)
[2]The TMF-2 Orica Saddle Dam is a single-stage dam.
[3]Dam is currently a single-stage dam with the intention to raise it using the centerline method.
[4]Mineral Journal Research Services (1996)
[5]Center for Science in Public Participation (2022)
[6]Tetra Tech Canada (2021)
[7]The South Embankment is a downstream dam.
[8]The East and West Embankments are centerline dams.
[9]Klohn Crippen Berger (2021a)
[10]BGC Engineering Inc. (2021)
[11]Lighthill (2014)
[12]SNC Lavalin (2021)
[13]Klohn Crippen Berger (2016)
[14]Klohn Crippen Berger (2021b)
[15]Lighthill (2021)
[16]Ashlu Gold Mine (1984)
[17]Tetra Tech Canada (2014)
[18]Ash (1986)
[19]Horton and Kempe (2001)
[20]Roughstock Mining Services LLC (2020)
[21]Clarke et al. (2021)

The objective of this report is to determine the raise categories from the sparse documentation for the 19 remaining mine sites. Before discussing the methodology for addressing the objective, I will first review the differences between tailings dams and water-retention dams, the chief methods of construction of tailings dams (upstream, downstream, centerline), the failure of tailings dams by static and seismic liquefaction, the greater vulnerability to failure of upstream dams, and alternative methods of construction of tailings dams (hybrid, single-stage, filtered-tailings stack). The review of tailings and tailings dams will be followed by a review of the Global Tailings Portal, which is the only existing global tailings dam database, although it is far from complete. More complete background on tailings and tailings dams can be found in the textbook Planning, Analysis and Design of Tailings Dams by Vick (1990).

REVIEW OF TAILINGS AND 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, as mentioned earlier, 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 more 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 (2015) 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 will be discussed further in the section on the Global Tailings Portal.

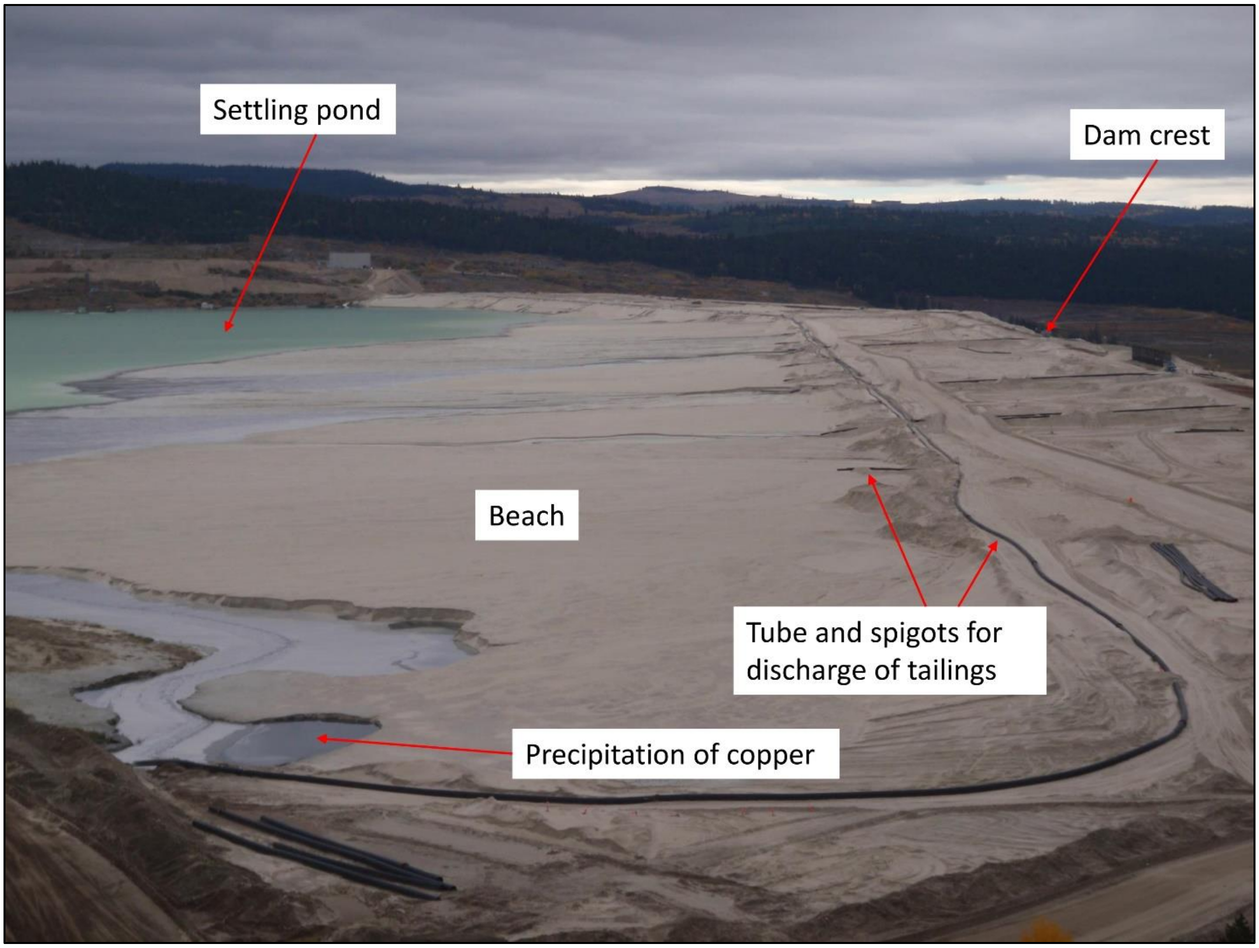

Figure 1. In conventional tailings management, tailings and water from the ore processing plant are injected in the upstream direction from spigots along the dam crest. The coarser tailings settle closer to the dam crest to form a beach. The finer tailings and water travel farther upstream where the 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.

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 exhausted open pit. Typically, a tailings dam is expected to confine the toxic tailings in perpetuity, although normally the 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 (2014b) 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."

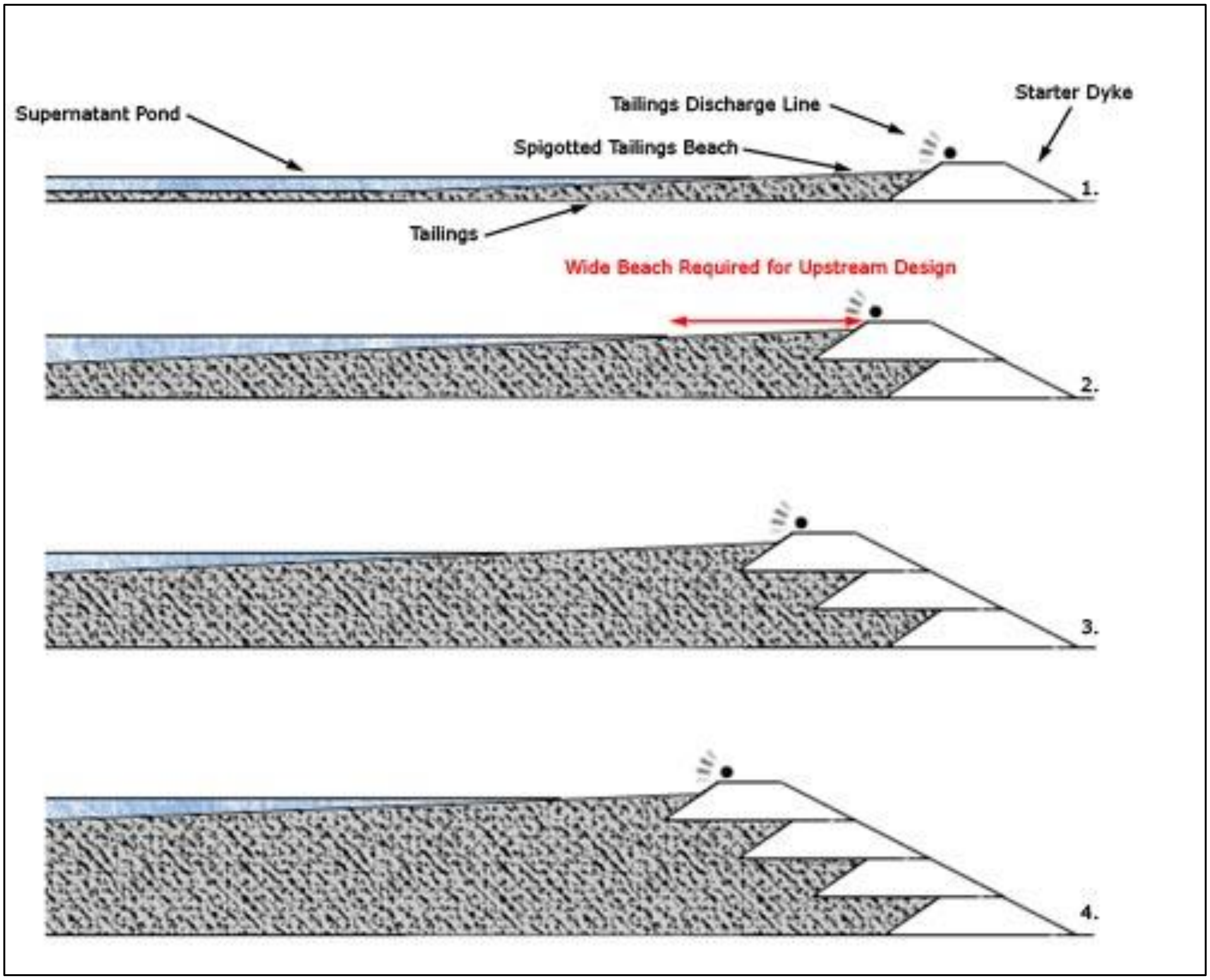

Figure 2a. In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. Dikes can be constructed with mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (with proper compaction). The advantage of 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. An adequate tailings beach is critical to maintain a low water table beneath the dam. Figure from TailPro Consulting (2022).

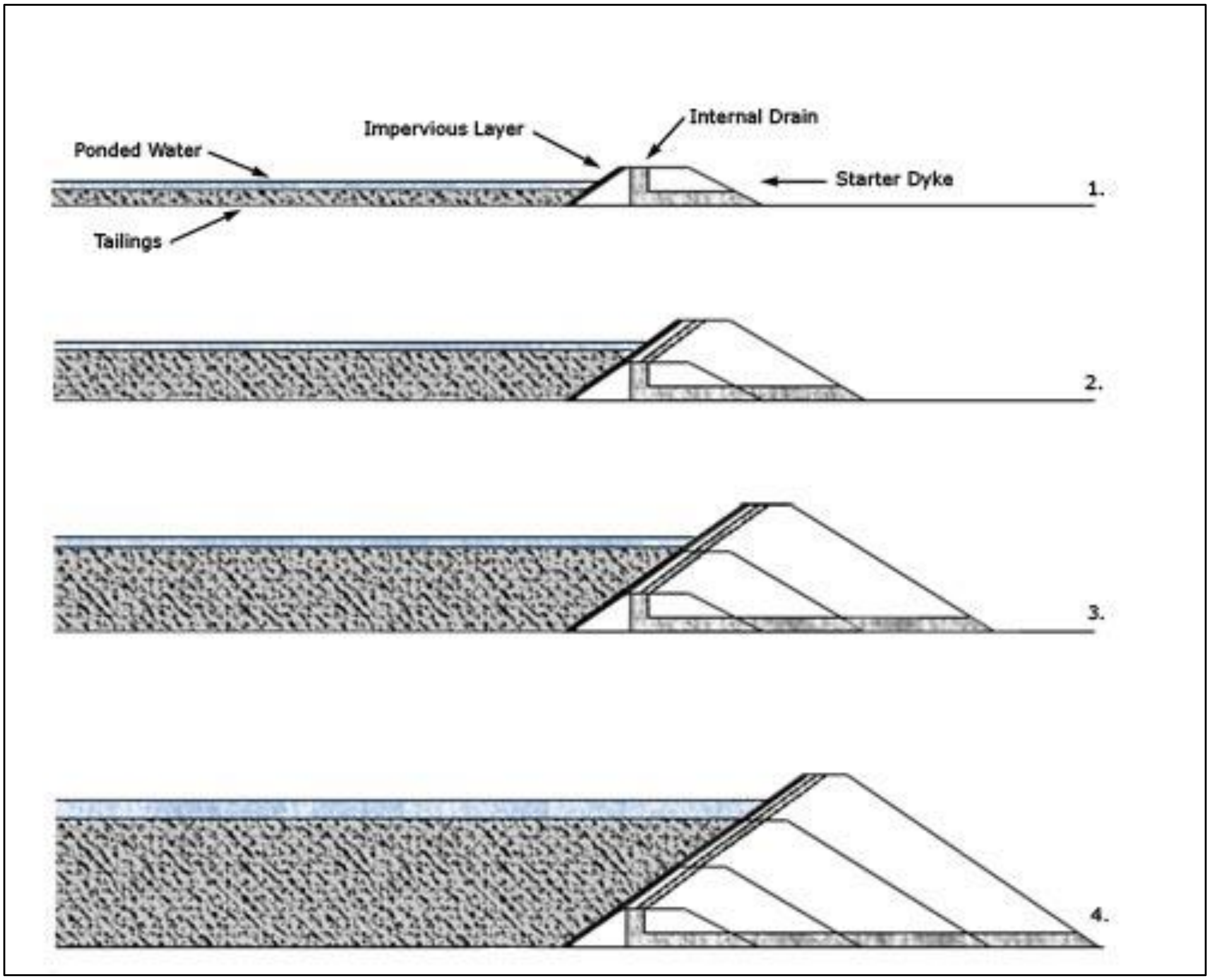

Figure 2b. In the downstream construction method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. Dikes can be constructed from mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (with proper compaction). The resistance 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. 2a and 2b). Figure from TailPro Consulting (2022).

Chief 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. 1). The discharge results in the separation of the sizes of tailings by gravity. The larger sands settle closer to the dam to form a beach. The smaller slimes and water travel farther from the dam to form a settling pond where the slimes slowly settle out of suspension. Typically, water is reclaimed from the settling pond and pumped back into the mining operation. It should be noted that the beach is essential for maintaining a low water table within the dam.

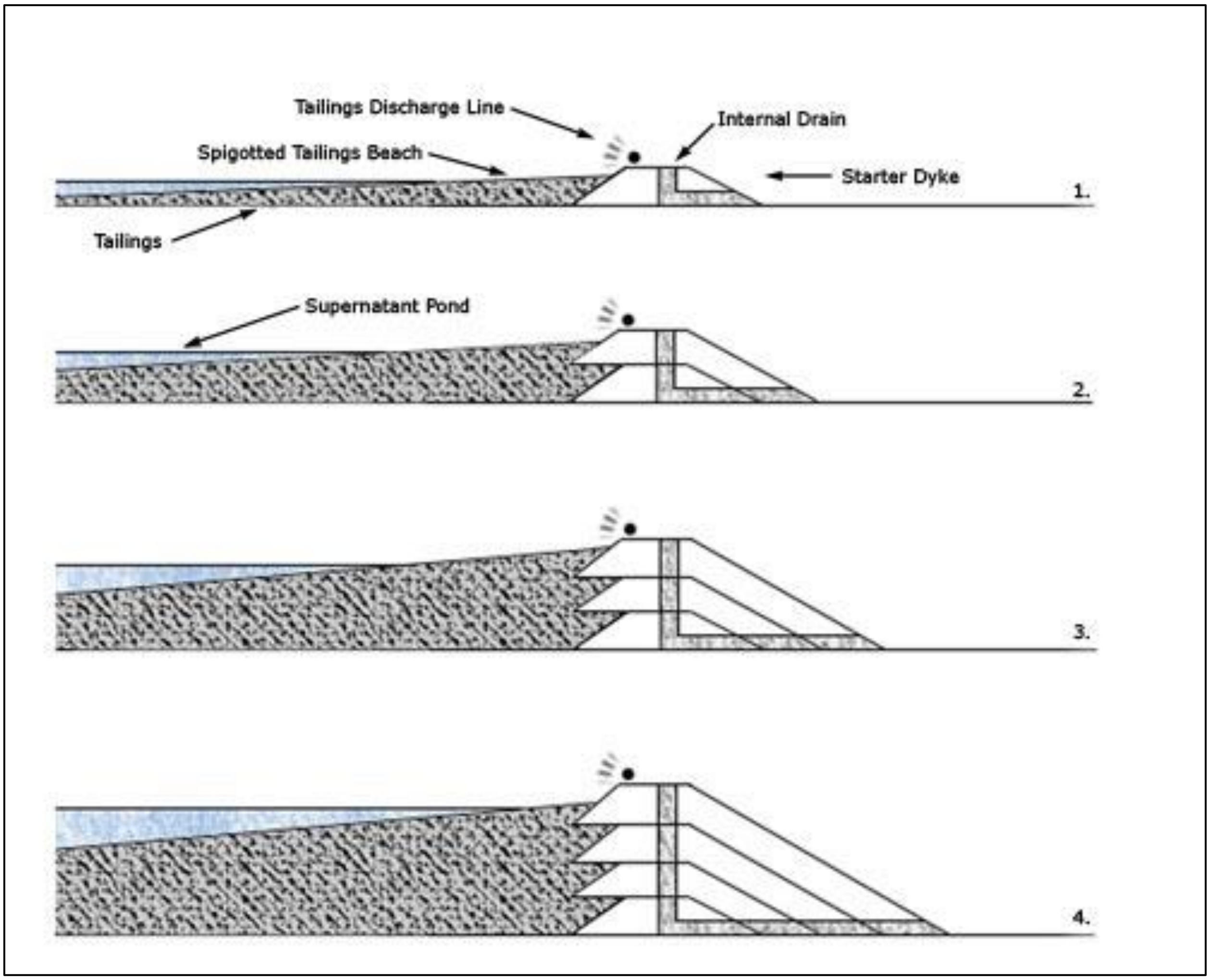

Figure 2c. In the centerline construction method, successive dikes are constructed by placing construction material on the beach and on the slope downstream of the previous dike. The central lines of the raises coincide as the dam is built upwards. Dikes can be constructed from mine waste rock, natural soil, natural rockfill, or the coarser fraction of tailings (with proper compaction). The centerline method is intermediate between the upstream and downstream methods (see Figs. 2a-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).

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, natural rockfill, mine waste rock or the tailings from an earlier episode of ore processing (see Figs. 2a-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. 2a). The downstream construction method is the most expensive since it requires the most construction material (compare Figs. 2a and 2b). 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. 2a-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. 2c).

Failure of Tailings Dams by Static and Seismic Liquefaction

Common causes of failures of tailings dams are seismic and static liquefaction. 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).

A normal stress means any stress that is acting perpendicular to a surface (see Fig. 3). 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. 3). The normal stress without subtracting the pore water pressure is also called the total stress.

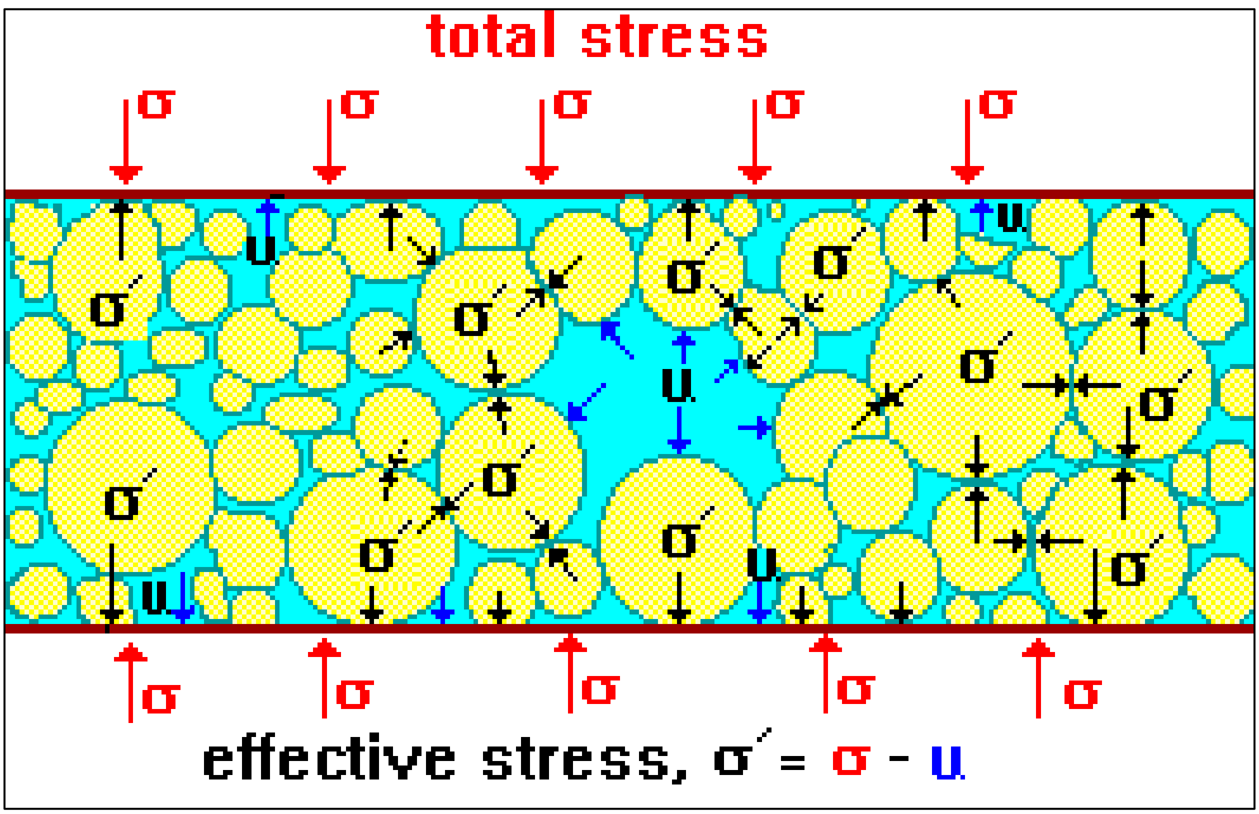

Figure 3. The effective stress in soil is equal to the total stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other. Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress. Figure from GeotechniCAL (2022).

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 (see Fig. 1). The weight of the solid particles creates a normal stress, so that the particles will consolidate under their own weight. The amount and rate of consolidation is determined by the effective stress, that is, the extent to which the particles are interacting with each another. Sufficient water pressure can offset the normal stress, so that little consolidation could occur and at a slow rate.

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. 3). In the diagram on the left-hand side of Fig. 4, 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. 4), 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.

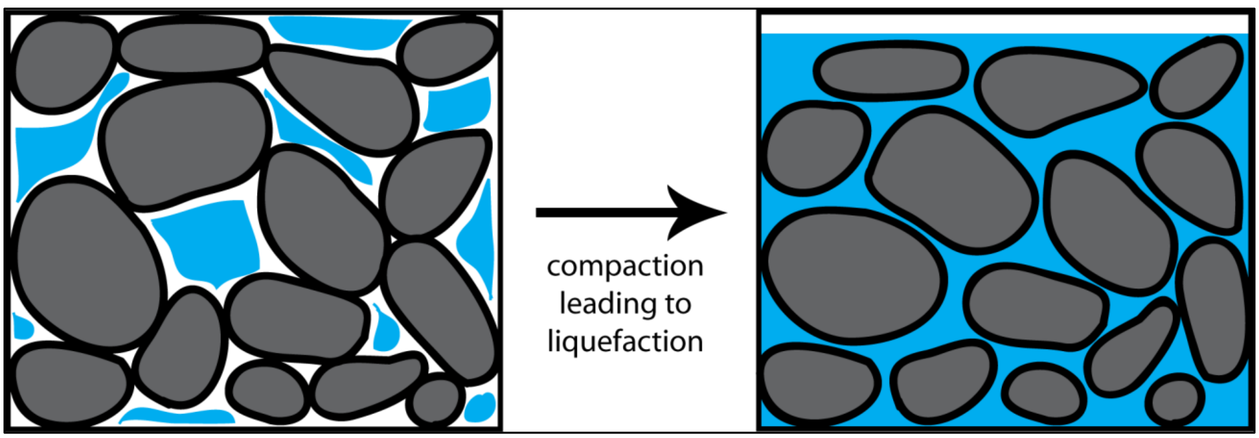

Figure 4. In the diagram on the left, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other, so that the load is supported by the particles (and partially by the water). Loose-packing means that the soil is in a contractive state, so that 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. 3). 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).

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. 4). 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. 3). 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. Conventional tailings storage facilities are especially susceptible to liquefaction because of the deposition of tailings by hydraulic discharge without subsequent compaction (see Fig. 1). 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). 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. 1).

Vulnerability to Failure of Upstream Dams

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. 2a). 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. 2c). 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. 2b). 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. 2a; 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 above, the upstream construction method is prohibited under all circumstances in Brazil (AMN, 2019), Chile (Ministerio de Minería (Chile) [Ministry of Mining (Chile)], 2007), Ecuador (Ministerio de Energía y Recursos Naturales No Renovables (Ecuador) [Ministry of Energy and Non Renewable Natural Resources (Ecuador)], 2020), and Peru (Sistema Nacional de Información Ambiental (Perú) [National System of Environmental Information (Peru)], 2014).

Alternative Methods of Construction of Tailings Dams

The most important alternative method for storing tailings involves filtering the tailings before they are shipped to the tailings storage facility. Filtered tailings technology dewaters the tailings to water contents less than about 25%, below which they behave more like a moist soil than a wet slurry (Klohn Crippen Berger, 2017). The primary purpose of filtering is to reduce the likelihood of liquefaction by making it possible to compact the tailings into a dilative state, from which they will tend to expand, rather than contract, following disturbance. Filtered tailings storage facilities or filtered-tailings stacks are sometimes referred to as “dry stacks.” However, this is non-standard terminology because the tailings are not literally dry and, if they were, they could not be properly compacted.

Figure 3.5 Schematic of a Filtered Tailings Facility

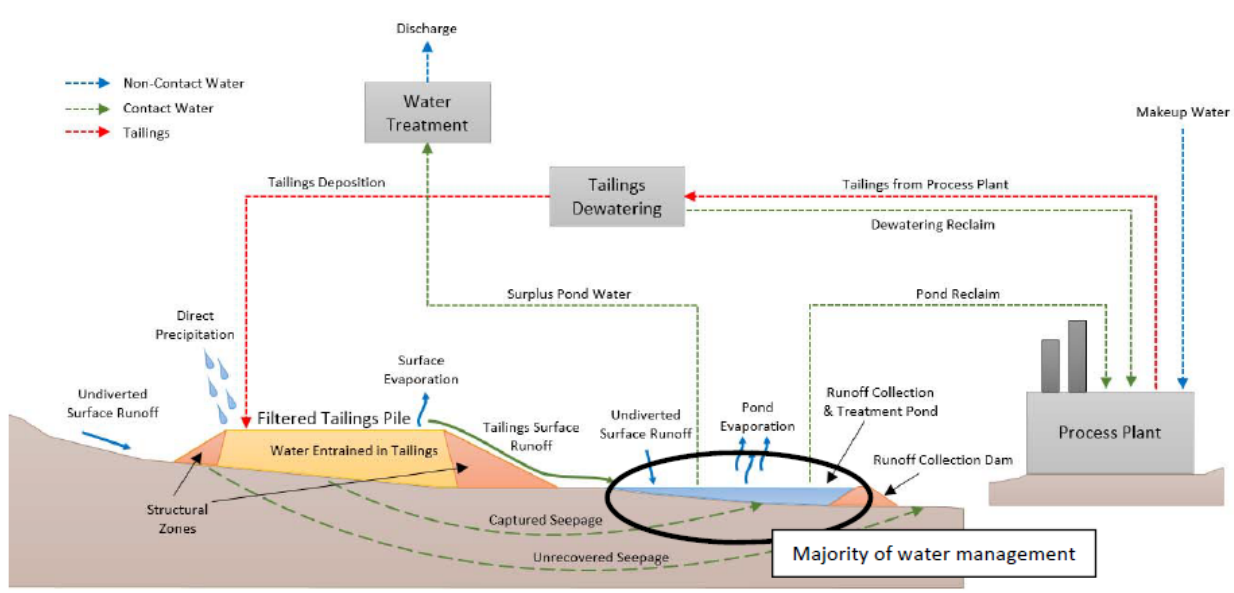

Figure 5. Based on current filter press technology, target water contents of 15% (typically required for adequate compaction) cannot be consistently met. Even if filtered tailings leave the filter presses with the target water content, they can be rewetted by precipitation. The standard response is to place the tailings that are too wet for adequate compaction in the center of the filtered tailings stack and to surround the wet tailings with “structural zones” constructed out of tailings that have the target water content for adequate compaction. The structural zone is a type of dam and should be designed to meet dam safety regulations. Figure from Klohn Crippen Berger (2017).

Filtered tailings storage facilities are not free-standing facilities and still require a dam for confinement of the tailings. Based on current filtering technology, it is not possible to consistently meet target water contents (typically 15%), especially on account of ore heterogeneity. Even if the tailings leave the filter presses with the target water content, they can still be rewetted by precipitation or surface runoff. The standard response is to place the tailings that are too wet for adequate compaction in the center of the filtered tailings stack and to surround the wet tailings with “structural zones” constructed out of tailings that have the target water content for adequate compaction (see Fig. 5). The structural zone is a type of dam and should be designed to meet dam safety regulations. Sometimes waste rock or natural rockfill are used to construct the structural zone of a filtered tailings storage facility.

A minor alternative construction method is that all raises do not have to be either upstream, downstream or centerline (see Figs. 2a-c), but can be any mix of the three. Such dams are known as hybrid dams. It should be noted that, if a multiple-raise dam has a single raise using the upstream method, then uncompacted tailings are present beneath the dam (see Fig. 2a), and the tailings dam should be regarded as unusually vulnerable to failure. The final alternative is that a tailings dam could be constructed as a single stage, much in the manner of a water-retention dam. Sometimes tailings dams are intended to be a single stage and sometimes the raises are never carried out after the starter dike is constructed (see Figs. 2a-c). It should be noted that, even when a tailings dam is constructed in the same way as a water-retention dam, it is still the case that the tailings dam can never be dismantled, although, at some point, inspection and maintenance will cease.

GLOBAL TAILINGS PORTAL

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).

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 volume, but not 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, as a single 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 in Minnesota Department of Natural Resources (2021) and the toe elevation in Barr Engineering (2019)).

Just as with the other databases, the Global Tailings Portal cannot be regarded as complete. For comparison, besides the USA, there are also databases of existing tailings dams for Brazil (ANM, 2022), Chile (SNGM, 2022), Mexico (Secretaría de Medio Ambiente y Recursos Naturales (México) [Secretariat of Environment and Natural Resources (Mexico)], 2021), Peru (CooperAcción, 2022) and Spain (Rodríguez Pacheco and Gómez De Las Heras, 2006; IGME, 2022). These databases list 889, 757, 585, 417, 988 and 1402 tailings dams for Brazil, Chile, Mexico, Peru, Spain, and the USA, respectively. The recovery in the Global Tailings Portal is very uneven, since it is 149 (16.8% of the above total), 34 (4.5% of the above total), 39 (6.7% of the above total), 77 (18.5% of the above total), 4 (0.4% of the above total), and 235 (16.8% of the above total) 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. Note that the Inventory of Large Dams in Canada (Canadian Dam Association, 2019a-b) does not include any tailings dams.

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 maximum height, the current tailings storage, the raise type, the raise category, 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. 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).

For the first time, the analysis by Franks et al. (2021) quantified the greater risk posed by upstream dams. 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) established that upstream dams have increased stability issues, even in cases where the stability issues did not proceed to dam failure (see Fig. 6). 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.” Further information about the Global Tailings Portal and the analysis by Franks et al. (2021) will be provided in the Results and Discussion sections.

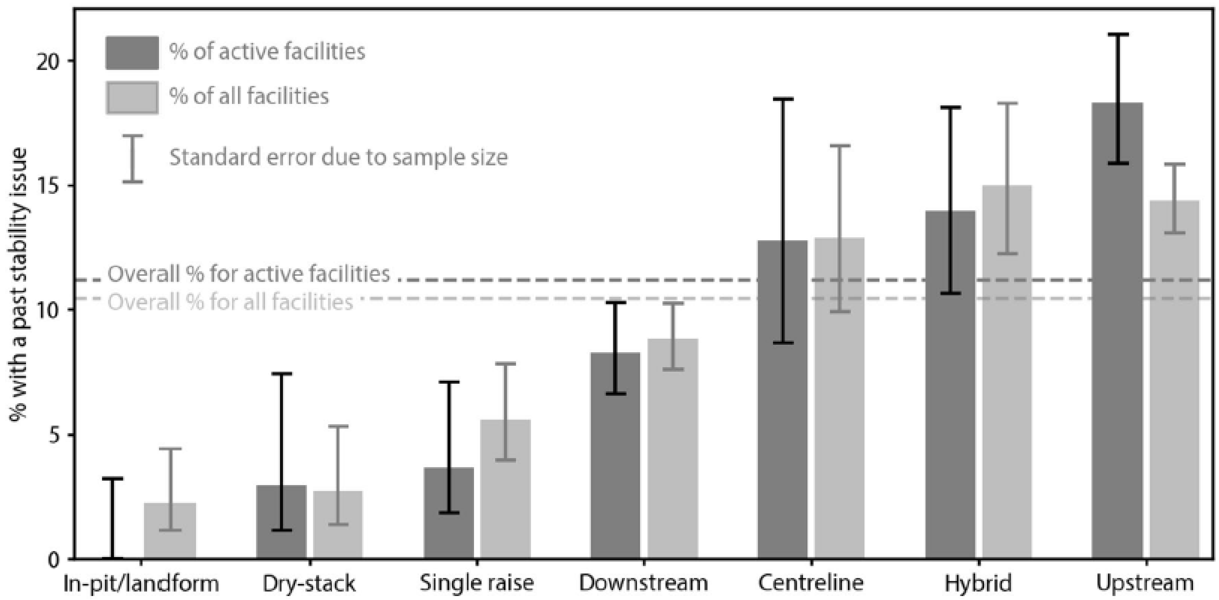

Figure 3. Stability of tailings facilities. Proportion of facilities with a stability issue by raise type. Error bar lengths are binomial confidence intervals for the subsample represented by each bar, showing ± 1 standard error (approximately 68%).

Figure 6. 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.” By contrast, the likelihood of a stability issue in an active tailings storage facility that uses a single-stage dam is only 3.6%. Thus, single-stage dams are nearly as safe as filtered-tailings stacks and safer than all of the common methods of dam construction, including hybrid dams. 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).

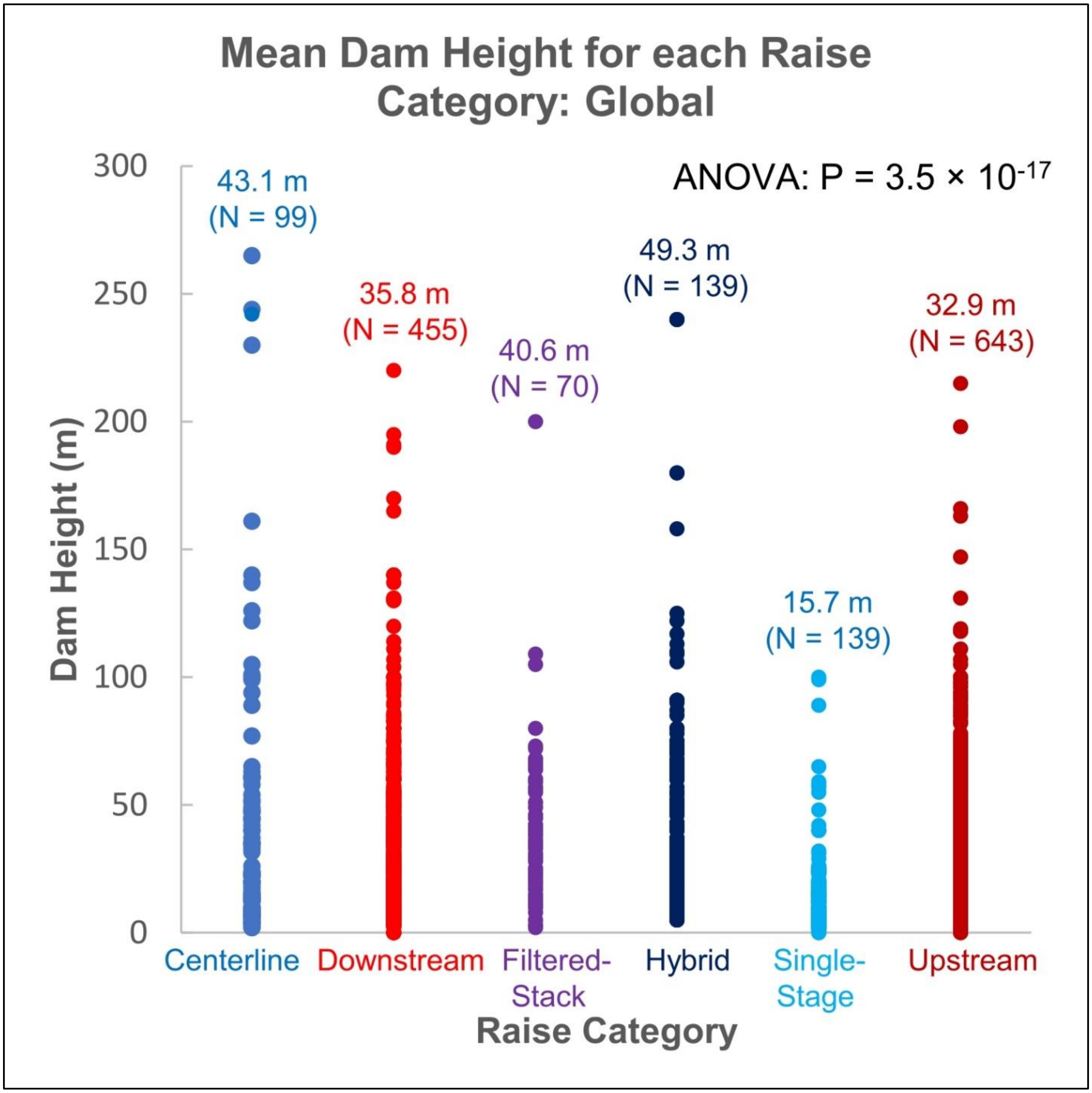

Figure 7. The Global Tailings Portal (Franks et al., 2021; GRID-Arendal, 2022) considers six raise categories for tailings storage facilities, which are centerline (see Fig. 2c), downstream (see Fig. 2b), filtered-stack (see Fig. 5), hybrid (combination of upstream, downstream and/or centerline raises), single-stage, and upstream (see Fig. 2a). As expected, single-stage dams are by far the shortest. Thus, in the absence of other information, tailings dams with heights less than about 25 meters could be assumed to be single-stage dams. According to the single-factor Analysis of Variance (ANOVA) test, $P = 3.5 \times 10^{-17}$ is the probability that all dam heights are drawn from the same population.

METHODOLOGY

The most definitive methodology for determination of the raise category is that sometimes the sparse documentation for a particular mine site includes an obscure, but explicit reference, to the raise category. The second most definitive methodology is that sometimes the sparse documentation includes a cross-section, so that the raise category could be determined by comparison with standard cross-sections for upstream, downstream and centerline dams (see Figs. 2a-c). The third methodology relates to the determination of the presence of a single-stage dam. Single-stage dams should tend to be shorter than other types of tailings dams. The use of the Global Tailings Portal showed that the mean dam heights for centerline, downstream, filtered-stack, hybrid, single-stage and upstream dams are 43.1 meters, 35.8 meters, 40.6 meters, 49.3 meters, 15.7 meters, and 32.9 meters, respectively (see Fig. 7), in which $P = 3.5 \times 10^{-17}$ is the probability that all dam heights are drawn from the same population, according to the single-factor Analysis of Variance (ANOVA) test. Finally, single-stage dams would be more likely to be constructed from natural materials (rockfill or earthfill) since mine waste rock and tailings would be less likely to exist at the time of construction of the starter dike, unless they were available from a previous episode of extraction or ore processing. A caution is that the distinction between mine waste rock (rock that is removed to reach the ore body) and other sources of rock ("natural rockfill") is not always clear in the available documentation, nor is such a distinction necessarily made in construction practice.

RESULTS

Explicit References to Raise Category

Out of the 19 mine sites (see Table 1), six include explicit reference to the raise category. According to Mineral Journal Research Services (1996), the "method of dam construction" at the Mineral King site is "centreline," and according to Center for Science in Public Participation (2022), the "dam type" is "centerline" (see Table 1). With regard to the Quinsam – North Pit site, Tetra Tech Canada (2021) states that "A combination of centerline and downstream raise methods were used to construct the dams … The North Embankment is a combination of a downstream and centerline constructed dam … The South Embankment is a downstream constructed dam … The East Embankment is a centerline dam … The West Embankment is a centerline dam …" (see Table 1). According to BGC Engineering Inc. (2021), at the Silvertip mine site, "The TRSF [Tailings and Rock Storage Facility] is being constructed bottom up as a sidehill dump of compacted dry-filtered desulphidised tailings surrounded by an outer shell of compacted non-potentially acid generating (non-PAG) mine rock" (see Table 1). The explicit reference with respect to the Goldstream (Revelstoke) mine site is that the intended dam raise was never completed, so that the tailings dam remained as a single-stage dam. According to Klohn Crippen Berger (2016), "Klohn Leonoff Ltd. (KLL) were involved in the design and construction of the TSF [Tailings Storage Facility] from 1977 to 1992. From 1993 Klohn Crippen Consultants (KCC) were involved in the design of a tailings dam raise to El. 695.5 m (not completed) and annual reviews." With regard to the HVC – 7Day Pond mine site, Klohn Crippen Berger (2021b) listed the "construction method" as "unknown (believed single raise)" (see Table 1). The single-stage status of the tailings dam was reinforced by its low height of 6 meters (see Table 1 and Fig. 7).

In the case of the Valentine Mountain/Ashlu mine site (see Table 1), the explicit reference to a single-stage is really the omission of any mention of raising the dam. According to Ashlu Gold Mine (1984), "The tailings will be disposed of in a natural depression east of the mill building … Based on site visits by Klohn Leonoff, laboratory soil tests results and hydrologic analysis of the site, a dam 98 m long by 9 m high has been designed and constructed." The preceding quote would have been the obvious place to mention any future raises of the dam if any raises were intended. The single-stage status of the tailings dam was reinforced by its low height of 9 meters (see Table 1 and Fig. 7). According to information provided to BC Mining Law Reform and SkeenaWild Conservation Trust by the British Columbia Ministry of Energy, Mines and Low-Carbon Innovation, although there is a tailings dam at the Valentine Mountain/Ashlu mine site, no tailings were ever deposited. For that reason, the Valentine Mountain/Ashlu mine site was not included in the tailings storage database.

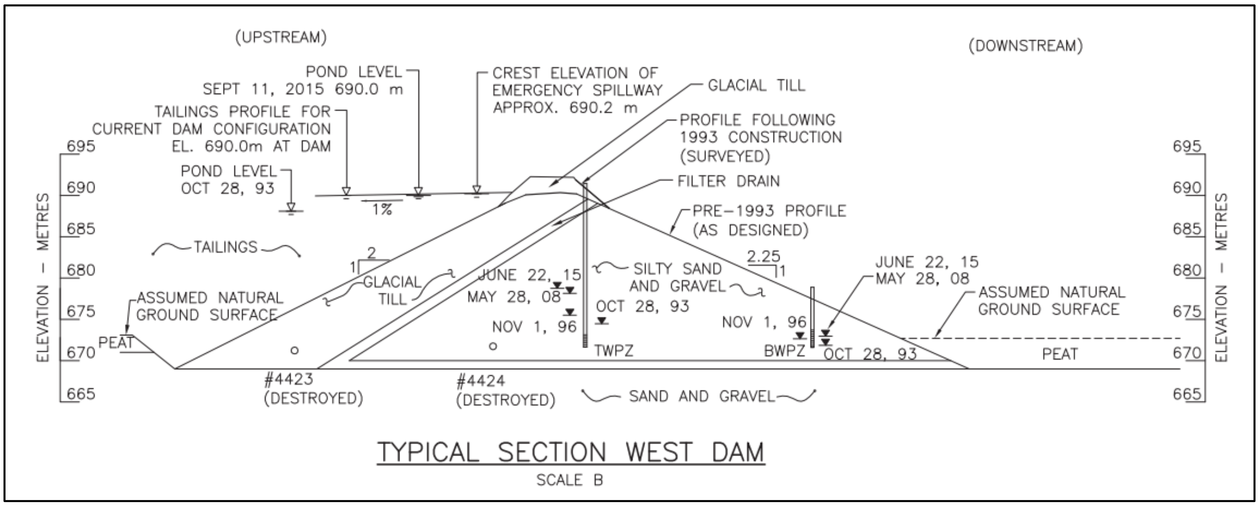

Figure 8a. The West Dam at the Goldstream (Revelstoke) mine site is 23 meters high and constructed from compacted earthfill. According to Klohn Crippen Berger (2016), planned dam raises were never completed. The above cross-section confirms that the West Dam is a single-stage dam. Portion of figure from Klohn Crippen Berger (2016).

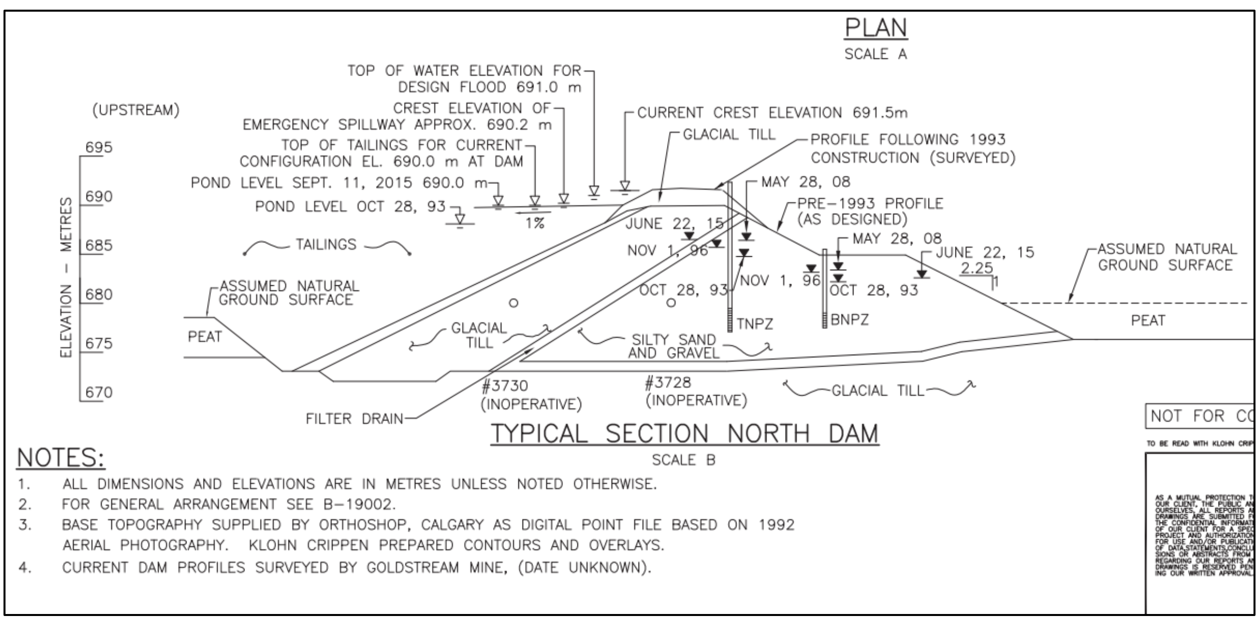

Figure 8b. The North Dam at the Goldstream (Revelstoke) mine site is 16 meters high and constructed from compacted earthfill. According to Klohn Crippen Berger (2016), planned dam raises were never completed. The above cross-section confirms that the North Dam is a single-stage dam. Portion of figure from Klohn Crippen Berger (2016).

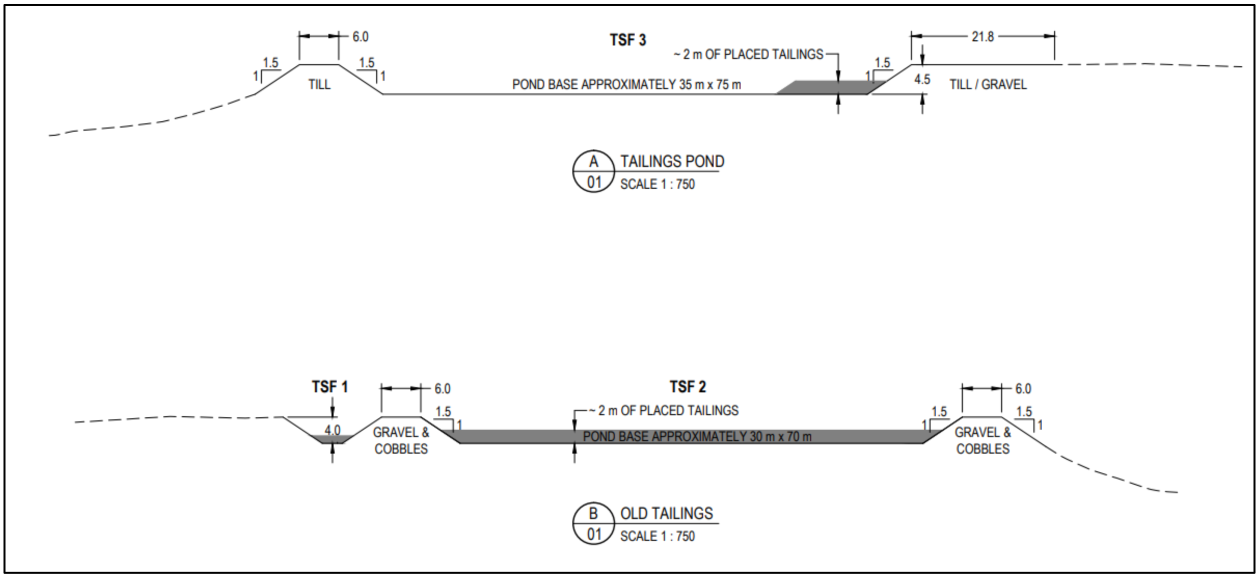

Figure 9. Based on the above cross-sections, the Yellowjacket mine site seems to include only single-stage dams. Portion of figure from Tetra Tech Canada (2014).

Raise Category based on Cross-Section

Out of the 19 mine sites (see Table 1), four include cross-sections that can be compared with the standard cross-sections of upstream, downstream and centerline dams (see Figs. 2a-c), including one overlap with the six mine sites discussed in the previous subsection. The Goldstream (Revelstoke) mine site was explicitly described as a single-stage dam by Klohn Crippen Berger (2016) who also presented cross-sections (see Figs. 8a-b). The cross-sections of the West Dam and North Dam show single-stage dams with no evidences of dam raises, aside from raising the dam crests by 1.5 meters in 1993 with a cap of glacial till (Klohn Crippen Berger, 2016; see Figs. 8a-b). The cross-sections of the tailings dams at the Yellowjacket mine site also show single-stage dams with no evidence of dam raises (Tetra Tech Canada, 2014; see Fig. 9). The single-stage status of the tailings dams at the Yellowjacket site is further reinforced by the low heights (4 meters for TSF1 and TSF2, 4.5 meters for TSF3) of the dams (see Table 1 and Fig. 9).

The Huckleberry mine site includes five tailings dams, two of which (TMF-2 Main Dam and East Pit Plug Dam) were clearly constructed using the centerline method based upon the cross-sections (Golder Associates, 2021; compare Figs. 10a-b with Fig. 2c). The successive raises were constructed by placing potentially acid-generating (PAG) rockfill on the tailings beach and non acid-generating (NAG) rockfill on the slope downstream of the previous dike with a final cap of NAG rockfill on the upstream side of the dam (see Figs. 10a-b). According to Golder Associates (2021), “The core [of the East Pit Plug Dam] is supported upstream by a waste rock shell.” As required in the centerline method, the central lines of the raises coincided as the dam was built upwards (compare Figs. 10a-b with Fig. 2c). The TMF-3 Main Dam and TMF-3 Saddle Dam are currently single-stage dams (based on the black lines in Figs. 10c-d) with the intention to raise to an “ultimate design crest” (based on the gray lines in Figs. 10c-d) using the centerline method (compare with Fig. 2c). The TMF-3 Main Dam and TMF-3 Saddle Dam will be raised by placing PAG waste rock on the tailings beach and NAG waste rock on the slope downstream of the previous dike with a final cap of NAG rockfill on the upstream side of the dam (see Figs. 10c-d). The current diagrams show the raises in a generalized manner with vertical slopes for the anticipated raises (see Figs. 10c-d). It should be understood that raises cannot actually be constructed with vertical slopes and that the construction material will be placed on top of the tailings beach (see Figs. 10a-b). Based on its cross-section (see Fig. 10e), the TMF-2 Orica Saddle Dam at the Huckleberry mine site is a single-stage dam with no raises (compare with Figs. 2a-c). The height of 10 meters is further evidence that the TMF-2 Orica Saddle Dam is a single-stage dam. As discussed in the Methodology, the discussion of the Huckleberry mine site by Golder Associates (2021) does not make a clear distinction between mine waste rock and other sources of rockfill.

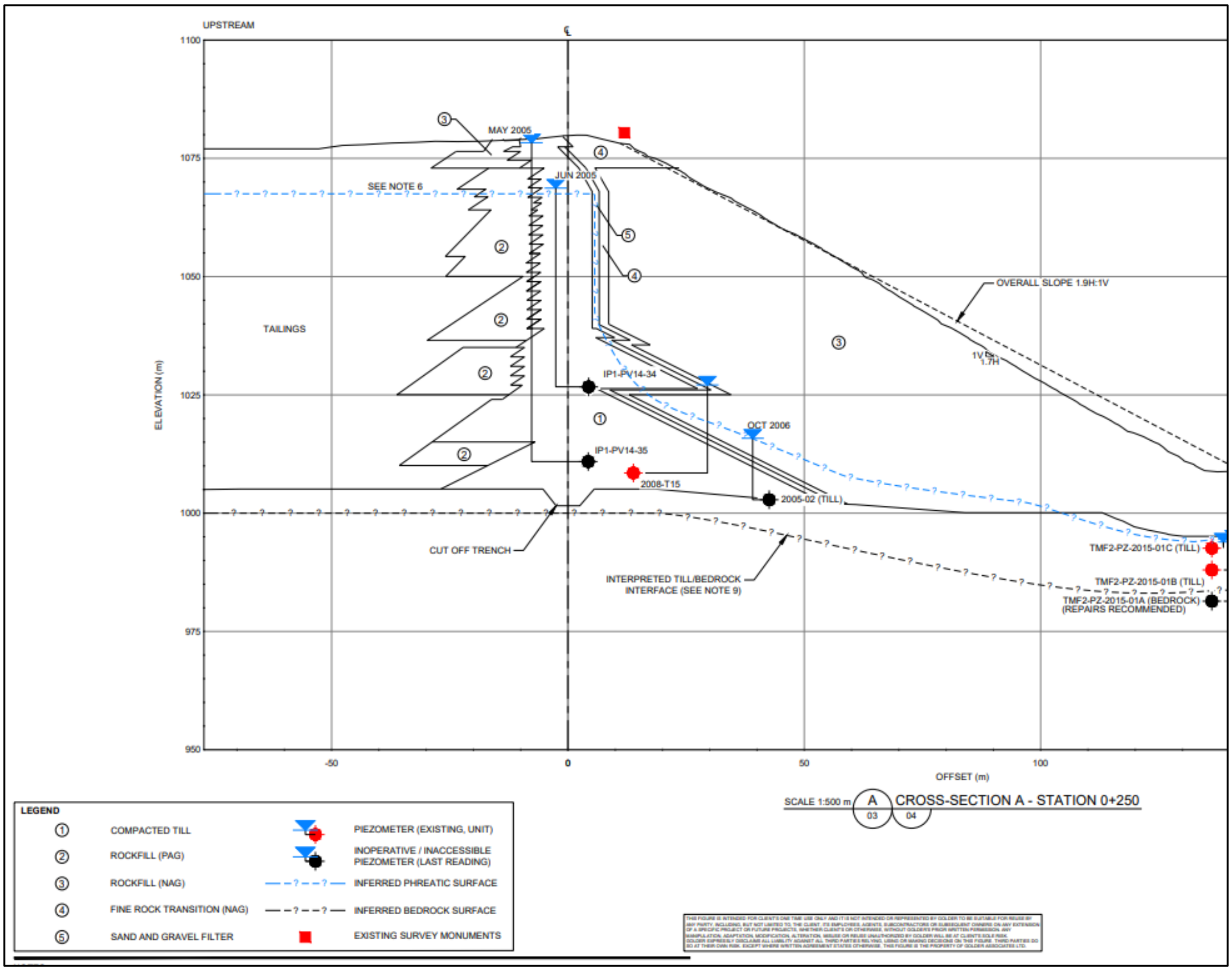

Figure 10a. The TMF-2 Main Dam at the Huckleberry mine site is 90 meters high and was constructed out of rockfill and glacial till. Based on the above cross-section, the dam was clearly raised using the centerline method (compare with Fig. 2c). Portion of figure from Golder Associates Ltd. (2021).

The two tailings dams at the QR Mine TSF site (called Cross Dyke and Tailings Dam) are clearly downstream dams based on the cross-sections (Klohn Crippen Berger, 2021a; compare Figs. 11a-b with Fig. 2b). Note that Cross Dyke retains some of the vulnerability to failure of an upstream dam since an upstream embankment of "sandy till" was placed on top of "existing waste and/or tailings" (Klohn Crippen Berger, 2021a; see Fig. 11a). The cross-section for Tailings Dam at QR Mine TSF has been divided into a downstream (left-hand) portion (see

Fig. 11b) and an upstream (right-hand) portion (see Fig. 11c). Tailings Dam also retains some of the vulnerability to failure of an upstream dam since PAG waste rock has been placed on top of tailings (see Fig. 11c).

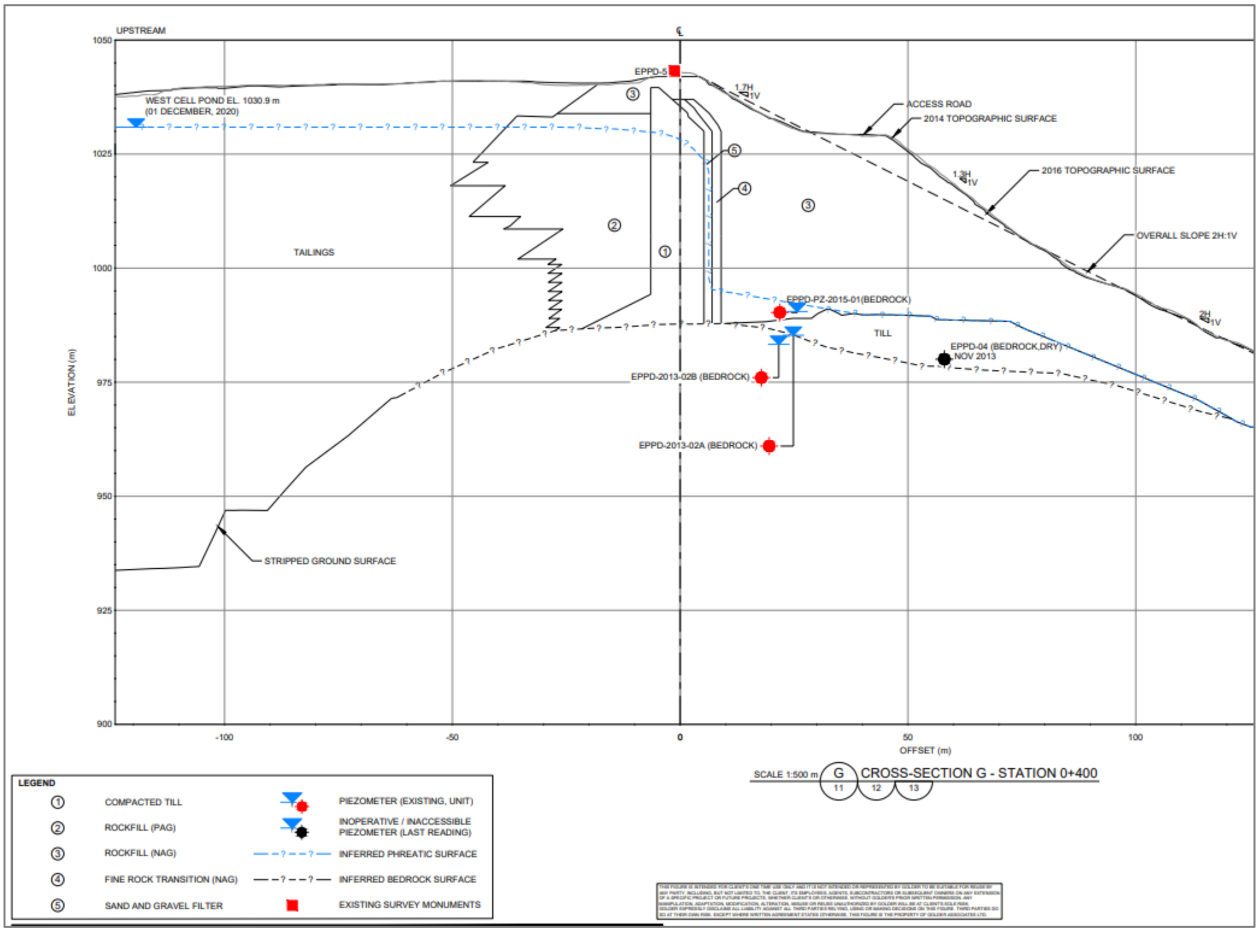

Figure 10b. The East Pit Plug Dam at the Huckleberry mine site was constructed out of natural rockfill, natural earthfill, and mine waste rock. Based on the above cross-section, the dam was clearly raised using the centerline method (compare with Fig. 2c). Portion of figure from Golder Associates Ltd. (2021).

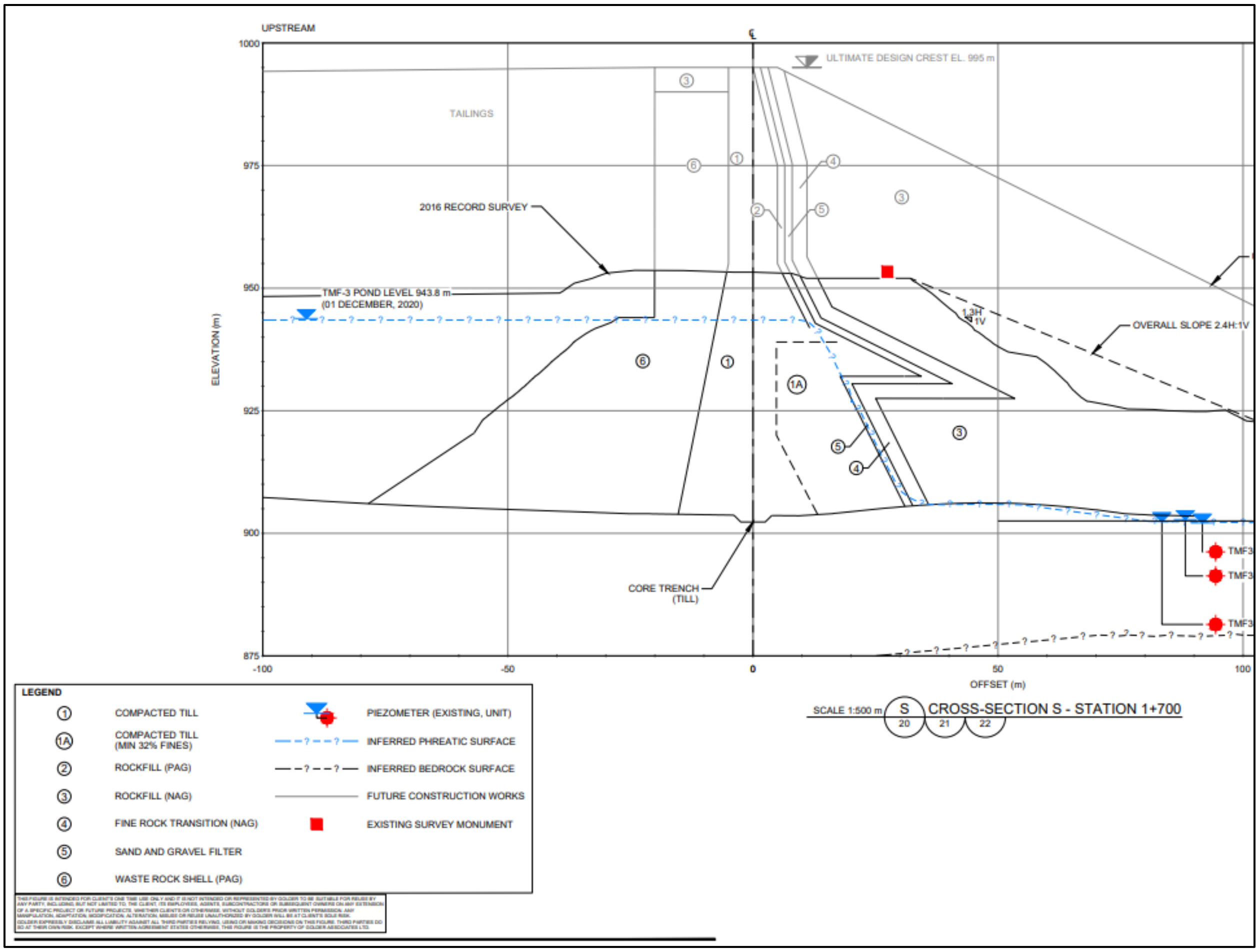

Figure 10c. The TMF-3 Saddle Dam at the Huckleberry mine site was constructed out of natural rockfill, natural earthfill, and mine waste rock. The dam is currently a single-stage dam (based on the black lines) with the intention to raise to an "ultimate design crest" (based on the gray lines) using the centerline method (compare with Fig. 2c). Portion of figure from Golder Associates Ltd. (2021).

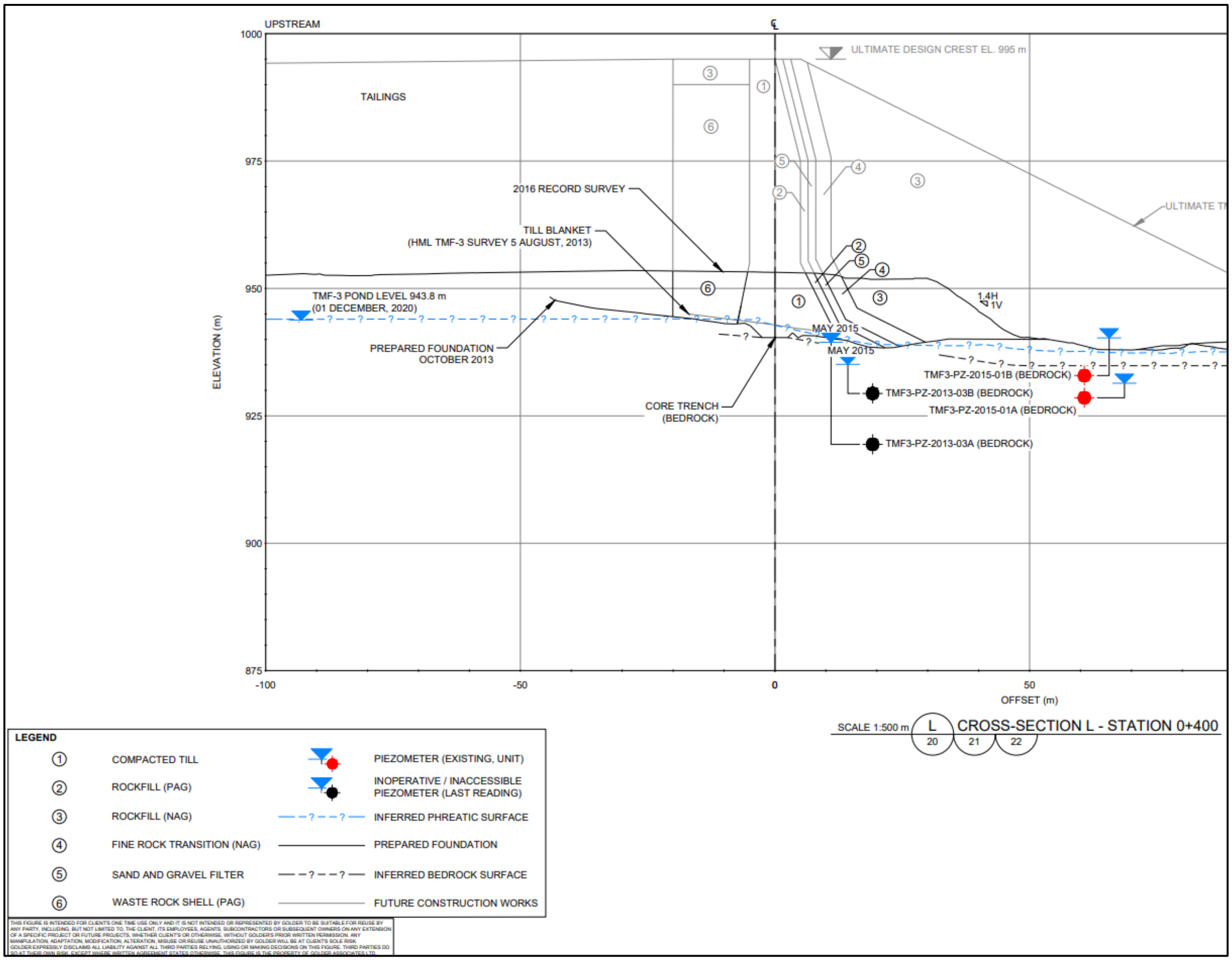

Figure 10d. The TMF-3 Saddle Dam at the Huckleberry mine site was constructed out of natural rockfill, natural earthfill, and mine waste rock. The dam is currently a single-stage dam (based on the black lines) with the intention to raise to an “ultimate design crest” (based on the gray lines) using the centerline method (compare with Fig. 2c). Portion of figure from Golder Associates Ltd. (2021).

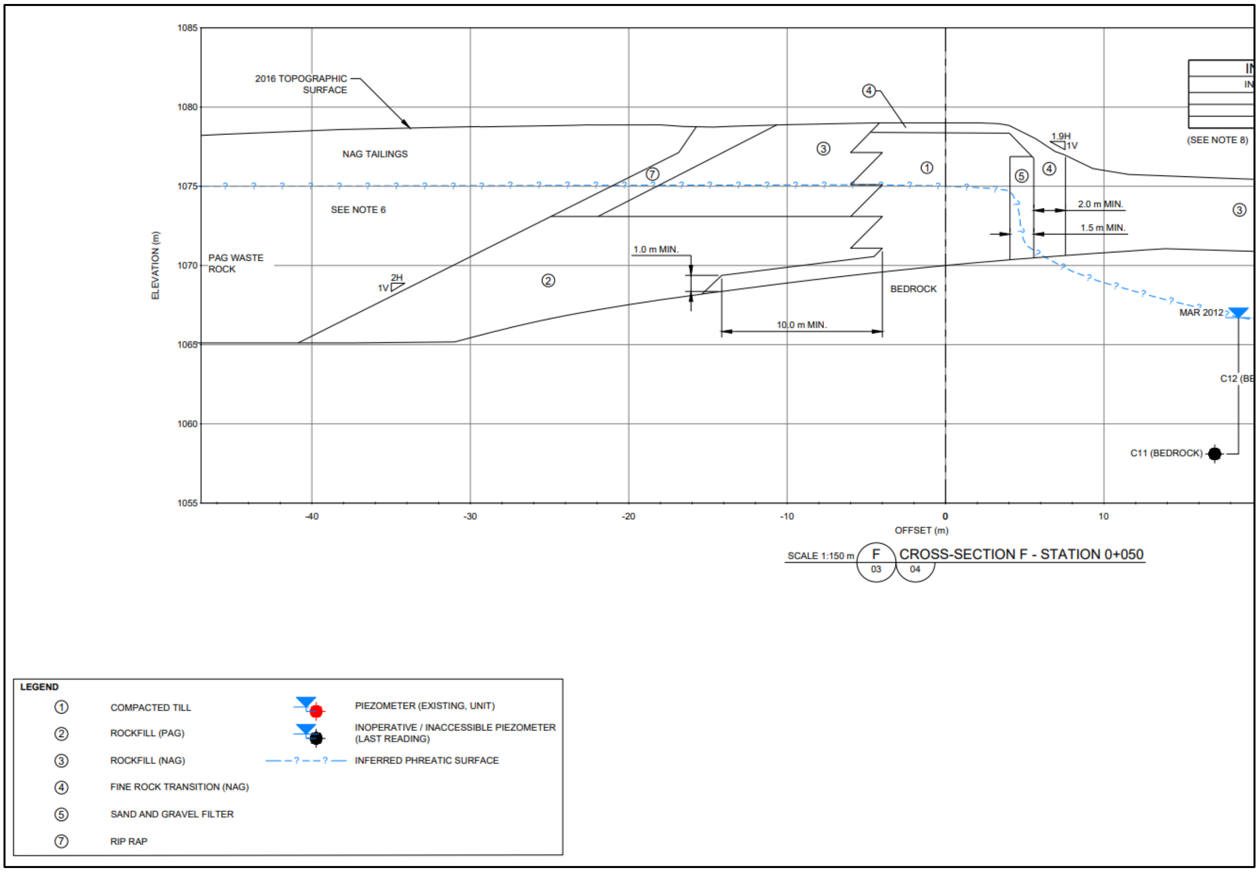

Figure 10e. The TMF-2 Orica Saddle Dam at the Huckleberry mine site is 10 meters high and was constructed out of rockfill and glacial till. Based on the above cross-section, the dam is clearly a single-stage dam with no raises (compare with Figs. 2a-c). The short height (10 meters) is further evidence that the TMF-2 Orica Saddle Dam is a single-stage dam (see Fig. 7). Portion of figure from Golder Associates Ltd. (2021).

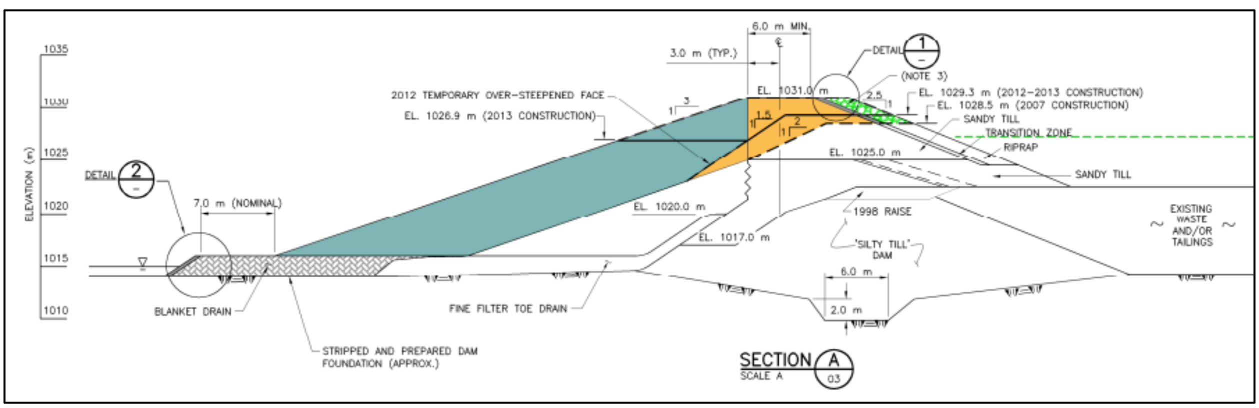

Figure 11a. The above cross-section shows progressive dam raises in the downstream direction (compare with Fig. 2b), indicating that the Cross Dyke at QR Mine TSF is a downstream dam. Note that the downstream dam retains some of the vulnerability to failure of an upstream dam since an upstream embankment of "sandy till" was placed on top of "existing waste and/or tailings" Portion of figure from Klohn Crippen Berger (2021a).

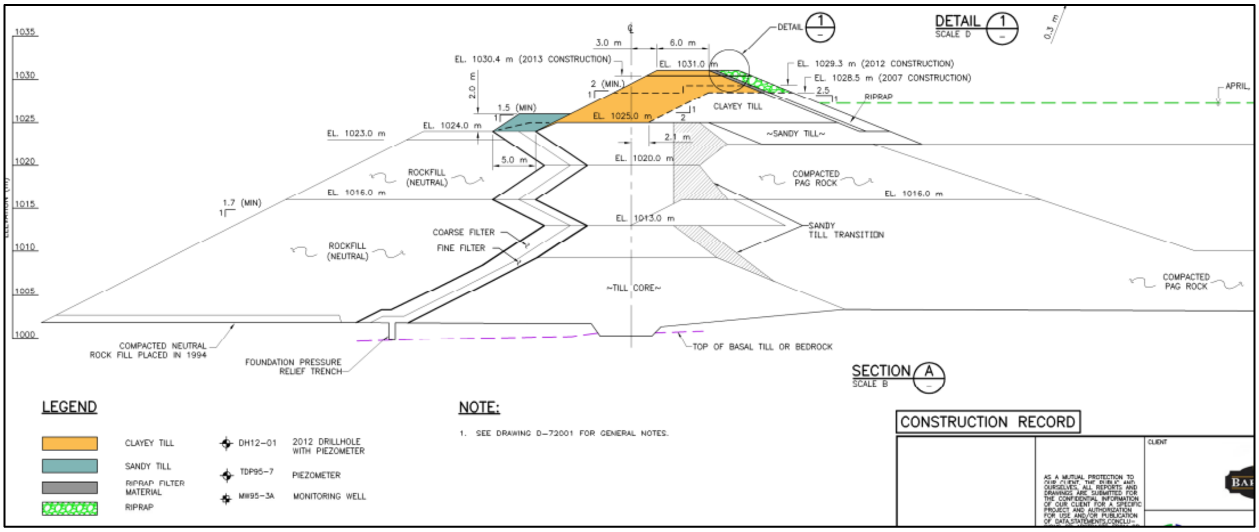

Figure 11b. The above cross-section shows progressive dam raises in the downstream direction (compare with Fig. 2b), indicating that the Tailings Dam at QR Mine TSF is a downstream dam. See upstream (right-hand-side) of cross-section continued in Fig. 11c). Portion of figure from Klohn Crippen Berger (2021a).

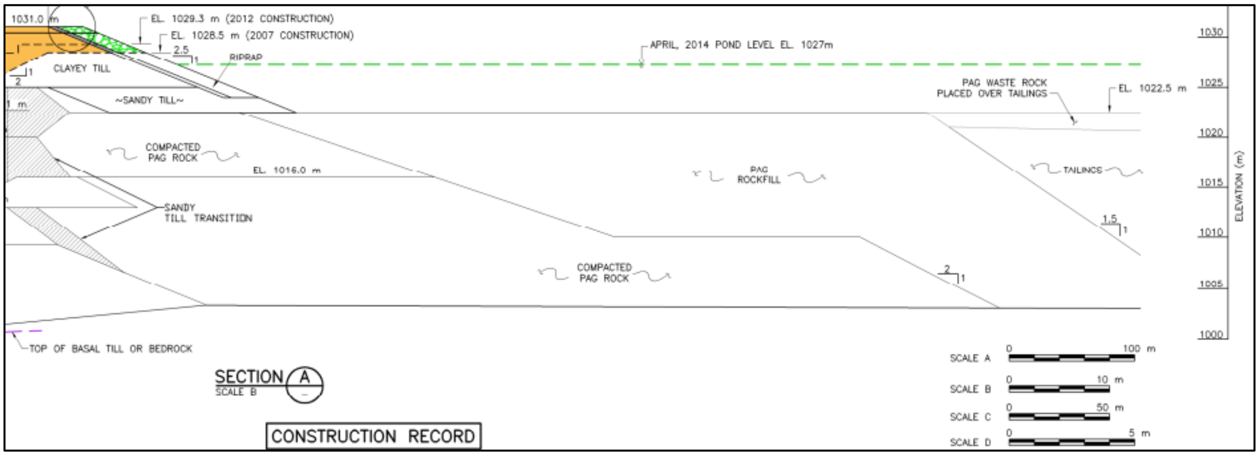

Figure 11c. The above cross-section shows progressive dam raises in the downstream direction (compare with Fig. 2b), indicating that the Tailings Dam at QR Mine TSF is a downstream dam. Note that the downstream dam retains some of the vulnerability to failure of an upstream dam since PAG (potentially acid generating) waste rock has been placed on top of tailings. See downstream (left-hand side) of cross-section continued in Fig. 11b. Portion of figure from Klohn Crippen Berger (2021a).

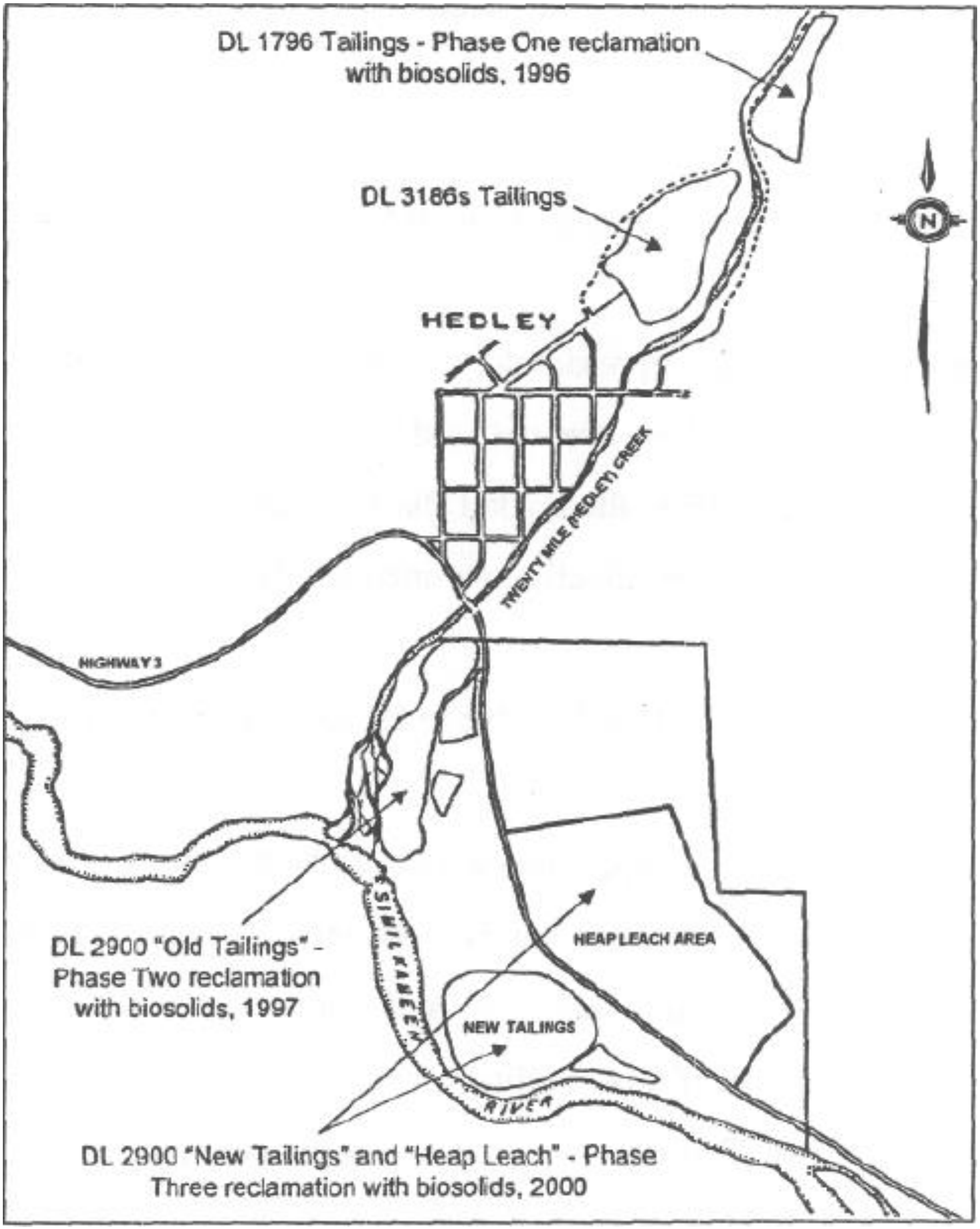

Figure 12. The tailings at the Candorado/Hedley site should be regarded as the least stable since the tailings were simply heaped with no dam or impoundment and no indication of dewatering and compaction. According to Horton and Kempe (2001), "Tailings previously deposited by the historic Mascot and Nickel Plate mining operations were mined, agglomerated with cement, progressively stacked into a seven hectare heap through a series of pads and leached with a cyanide solution to extract gold." The placement of the tailings along the banks of streams should be a matter of particular concern. Figure from Horton and Kempe (2001).

Raise Category based on Dam Height and Construction Material

Three additional mine sites were classified as having only single-stage dams based upon the dam height and construction material (see Table 1). The tailings dam at the May Mac (Bow/Boundary Falls) site is composed of natural earthfill with a maximum height of 12-15 meters (Lighthill, 2021; see Table 1), which is even shorter than the average height of a single-stage dam (see Table 1 and Fig. 7). The Good Friday TSF at the Coxey/Red Mountain/Rossland site is composed of glacial till and natural rockfill with a maximum height of 20 meters, while the Jumbo TSF is composed of natural rockfill with a maximum height of 28 meters (Lighthill, 2014; see Table 1). The tailings dams are taller than average for single-stage dams, but still shorter than would be average for upstream dams (32.9 meters; see Fig. 7). The tailings dam at the Gallowai/Bull River site is probably a single-stage dam since its height is 30 meters and the dam was constructed from glacial till (SNC Lavalin, 2021; see Table 1). It is noteworthy that none of the reports on the May Mac (Bow/Boundary Falls), Coxey/Red Mountain/Rossland or Gallowai/Bull River sites mentioned any possibility of dam raises after the initial construction (Lighthill, 2014, 2021; SNC Lavalin, 2021).

Raise Categories Classified as Other

There is one mine site that is classified as Other. At the Candorado/Hedley mine site, there are no engineered tailings facilities, but only free-standing heaps of tailings with no dams or impoundments of any kind (see Table 1 and Fig. 12). There is certainly no indication that the tailings were filtered (dewatered) and compacted, which would create the possibility of some geotechnical stabilization. According to the proposal by Ash (1986), "The tailings consist of 2 large piles … The tailings will be picked up by earth moving equipment, hauled to the agglomeration area, dumped into a hopper, conveyed to an agglomeration plant, and thence to leach pads where cyanide solutions, will be sprayed, percolated through, and collected for processing in a central processing plant." According to the most recent description, "Tailings previously deposited by the historic Mascot and Nickel Plate mining operations were mined, agglomerated with cement, progressively stacked into a seven hectare heap through a series of pads and leached with a cyanide solution to extract gold" (Horton and Kempe, 2001). The agglomeration with cement is a means of converting clay-sized tailings into pellets and should not be regarded as a means of stabilizing the tailings heaps. According to Ash (1986), "The tailings particles of the Hedley tailings piles are so finely-ground that they may be entirely classed as being 'clay-sized,' and cannot be heap-leached by normal means. However, by the process of agglomeration, blinding does not occur, excellent percolation characteristics may be maintained, and the pellets are porous, thus allowing the cyanide solution to pass directly through, dissolving and picking up all the 'exposed' gold. Agglomeration is the forming of semi-spherical pellets by combining tailings with cement and/or lime, and a small amount of water, rolling the mixture around … These pellets are then stacked by a stacking conveyor onto a large leach pad."

Raise Categories Classified as Unknown

There are six mine sites for which the raise categories remain unknown. At the present time, at the Dome Mountain mine site, all ore is shipped off-site for processing and tailings storage. According to the NI 43-101 Technical Report, "In early 2013, Gavin Mines submitted applications to amend their existing Mines Act and Environmental Management Act permits to authorize onsite milling and tailings storage. Due to various delays, including regulatory changes resulting from the 2014 Mount Polley tailings breach, the permit amendments remain outstanding. In 2016, stockpiled material was processed at Nicola Mining Inc.'s custom mill facility near the town of Merritt" (Roughstock Mining Services LLC, 2020). Clarke et al. (2021) confirmed that "The company [Blue Lagoon Resources Inc.] entered into a milling agreement with Nicola Mining Inc. in which ore will be trucked for processing at a mill west of Merritt." The current off-site milling is clearly related to historical extraction and the milling of stockpiled ore. Since there is a proposal to re-open the mine but with no publicly available description of the proposed tailings storage facilities, the raise category is classified as Unknown. The raise categories at the Lawyers/Cheni, Mount Copeland, New Privateer/Privateer/Zeballos, Northair and Taurus Gold sites are further classified as Unknown since there is no publicly available information on the tailings storage facilities (see Table 1).

DISCUSSION

Out of the 19 mine sites with tailings dams with unknown raise categories under consideration for a new tailings storage database for British Columbia, it was determined that two sites included centerline dams, one included hybrid (mixed centerline-downstream) dams, one site included downstream dams, one site included a filtered-tailings stack, seven included single-stage dams, one mine site was classified as Other, and the raise categories of the tailings dams at six of the mine sites remained unknown. The positive news is the preponderance of single-stage dams and the lack of upstream dams among the mine sites with known raise categories. The vulnerability to failure of upstream dams has already been discussed. 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 …" (see Fig. 6). By contrast, use of the same database as was used by Franks et al. (2021) shows that the likelihood of a stability issue in an active tailings storage facility that uses a single-stage dam is only 3.6% (see Fig. 6). Thus, single-stage dams are nearly as stable as filtered-tailings stacks and more stable than all of the common methods of dam construction, including hybrid dams (see Fig. 6).

A cautionary note is that, at one of the mine sites (QR Mine TSF; see Table 1 and Figs. 11a-c), part of the foundation for the new tailings dams was existing tailings or waste rock. There are probably other examples of tailings dams in British Columbia that have been constructed on top of tailings. Although it was not one of the mine sites investigated in this report, cross-sections of the tailings dams at the Table Mountain site appear in the same Dam Safety Inspection report as the Taurus Gold site (Tetra Tech, 2017). One of the Table Mountain cross-sections shows a single-stage dam apparently constructed on top of an existing single-stage dam and its impounded tailings (see Fig. 13). The zone numbering in Fig. 13 is not defined in Tetra Tech Canada (2017). The zone numbers are not being used in a standard way, since a more standard numbering is Zone 1 (earthfill core), Zone 2A (fine filter drain), Zone 2B (coarse filter drain), and Zone 2C (upstream filter) (Fell et al., 2015).

In some ways, these tailings dams constructed on top of existing tailings and waste rock could retain the vulnerability to failure of upstream dams (compare Figs. 11a-c and 13 with Fig. 2a). However, it is also possible that the tailings and waste rock were adequately drained and compacted prior to construction of the new tailings dams, so that the foundation is as good as any other dam foundation. It should be noted that the Global Tailings Portal includes no information about the dam foundation and that the raise category is chosen by the mining company, not by an independent body. For the upcoming database on tailings storage in British Columbia, it would probably be most informative if there were explanatory notes detailing the ways in which a non-upstream dam might have some of the vulnerability characteristics of an upstream dam.

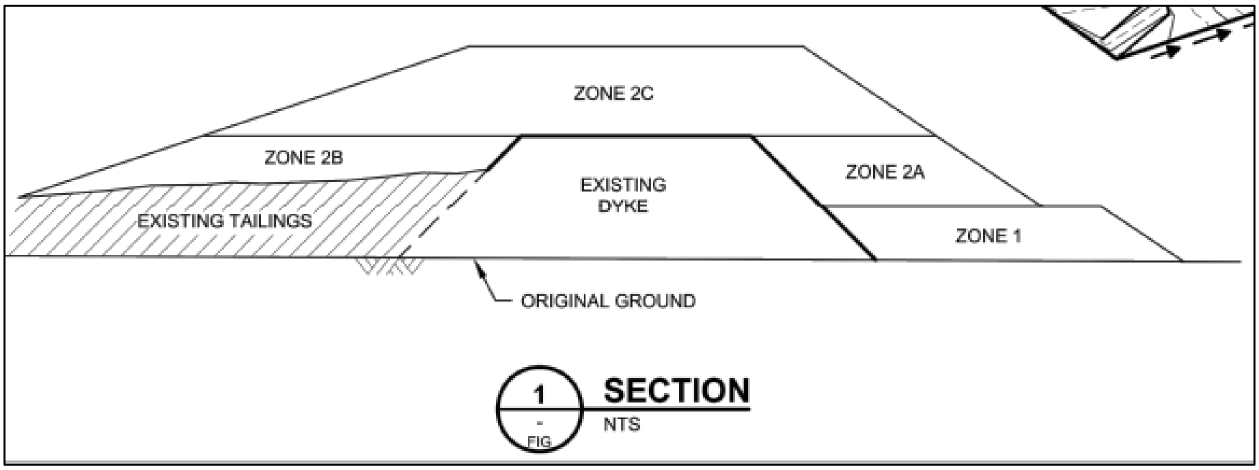

Figure 13. Based on the above cross-section, the Table Mountain site seems to include a single-stage dam constructed on top of and incorporating an existing dam with impounded tailings. The text (Tetra Tech Canada, 2017) does not clarify the meanings of the zones, which do not use standard nomenclature. Note that the presence of Zones 2B and 2C on top of "existing tailings" means that the Taurus Gold tailings dam has some of the vulnerability to failure of an upstream dam (compare with Fig. 2a). Portion of figure from Tetra Tech Canada (2017).

On the other hand, the greatest concern should not be upstream dams, but tailings that are simply sitting in heaps with no dam or impoundment of any kind, such as at the Candorado/Hedley mine site (see Table 1 and Fig. 12). Although the various heaps at the Candorado/Hedley mine site have now been reclaimed with biosolids (Horton and Kempe, 2001), there have been no measurements or modeling that have demonstrated the geotechnical stability of the heaps. In fact, Horton and Kempe (2001) have claimed only that "Forage establishment with biosolids was successful for all reclaimed tailings areas, improving their aesthetics and dust control." The placement of the tailings heaps along the banks of streams should be a matter of particular concern (see Fig. 12).

CONCLUSIONS

The conclusions of this report can be summarized as follows:

1) The Huckleberry and Mineral King sites include centerline dams.
2) The Quinsam – North Pit site includes hybrid (mixed centerline – downstream) dams.
3) The QR Mine TSF includes a downstream dam.
4) The Silvertip site includes a filtered tailings stack.

5) The Coxey/Red Mountain/Rossland, Gallowai/Bull River, Goldstream (Revelstoke), HVC - 7Day Pond, May Mac (Bow/Boundary Falls), Valentine Mountain/Ashlu, and Yellowjacket sites include single-stage dams.
6) In terms of raise categories, the Candorado/Hedley site is classified as Other, since the tailings are simply heaped with no dewatering or impoundment.
7) The raise categories are unknown at the Dome Mountain, Lawyers/Cheni, Mount Copeland, New Privateer/Privateer/Zeballos, Northair, and Taurus Gold sites.
8) None of the mine sites include upstream dams. However, the QR Mine TSF site retains some of the vulnerability to failure of upstream dams since some dam construction material has been placed on top of existing tailings or waste rock.

ABOUT THE AUTHOR

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