Evaluation of the Tailings Dam, Cyanide Use and Water Consumption at the Proposed Volta Grande Gold Project, Pará, Northern Brazil

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LIGHTNING SUMMARY

The proposed Volta Grande Gold Project includes a tailings dam along the banks of the Xingu River, a major tributary of the Amazon River in Pará, northern Brazil. The recycling of the cyanide leachate between the tailings reservoir and the ore processing plant has the potential to enrich the tailings water in antimony, arsenic and mercury. The dam has not been designed with any seismic safety criterion and with no study of local or regional seismicity. In the most-likely failure scenario, the initial runout of tailings would cover 41 kilometers with significant impact on the Arara de Volta Grande do Xingu indigenous land.

ABSTRACT

The Canadian company Belo Sun Mining has proposed the Volta Grande Gold Project, which would include the permanent storage of 35.43 million cubic meters of mine tailings and water behind a 44-meter high tailings dam along the banks of the Xingu River, a major tributary of the Amazon River in Pará, northern Brazil. The predicted water consumption is consistent with gold mining trends and would have little impact on the flow of the Xingu River. The water economy would be achieved by using the tailing reservoir to capture surface runoff, so that all tailings would be saturated and with seven meters of free water above the surface of the solid tailings. The capture of surface runoff is contrary to the mining industry trend of reducing the water stored in tailings reservoirs in order to reduce both the probability and consequences of dam failure. The dam has not been designed for any seismic safety criterion, in violation of Brazilian tailings dam regulations. There has been no study of local or regional seismicity, although geological faults have been mapped at the site of the tailings dam. The gold would be extracted with cyanide and the cyanide leachate would be exported to the tailings reservoir. There would be no downstream discharge from the tailings reservoir and the free water would be recycled to the ore processing plant with no water treatment. This recycling of cyanide leachate could result in tailings water that is highly enriched in antimony, arsenic and mercury. In the most-likely dam failure scenario (release of 28% of the stored tailings), the initial runout of tailings would cover 41 kilometers along the Xingu River with significant impact on the Arara de Volta Grande do Xingu indigenous land. Under the worst-case scenario (release of 100% of stored tailings), the initial runout would cover 98 kilometers along the Xingu River. Following the initial runout, normal fluvial processes would transport the tailings into the Amazon River and the Atlantic Ocean. There is no plan for safe closure of the tailings dam, except for draining the free water into a water storage pond. Although some corporate communications have indicated plans to pursue filtered tailings technology (reducing the water content to <25% before storage), this technology still has considerable technical challenges in areas of high rainfall.

TABLE OF CONTENTS

OVERVIEW

Belo Sun Mineração, a wholly-owned subsidiary of the Canadian company Belo Sun Mining, has proposed the construction of the Volta Grande Gold Project along the banks of the Xingu River, a major tributary of the Amazon River in the state of Pará in northern Brazil (see Figs. 1-2). The proposed gold mine would operate for 12 years and would use cyanide to extract gold from 3.5 million metric tons of ore per year with an average grade of 1.47 grams of gold per metric ton of ore (Brandt Meio Ambiente, 2016a). The mine would be located about 15 kilometers south of the Belo Monte dam (see Fig. 2), which was completed in November 2019 and which diverts 80% of the flow of the Xingu River for generation of hydroelectric power (Higgins, 2020). The proposed mine site would be about 12 kilometers southwest and about 16 kilometers west of the indigenous lands of the Paquiçamba and the Arara de Volta Grande do Xingu, respectively (see Fig. 2). The gold ore would be mined from two open pits, Grota Seca and Ouro Verde (see Fig. 3), each of which would be about 220 meters deep. The mining operation would not take water directly from the Xingu River, but would capture water from precipitation, surface runoff and tributaries of the Xingu River in two water storage ponds, Leste and Oeste, and in the tailings deposit (see Fig. 3; Brandt Meio Ambiente, 2016a).
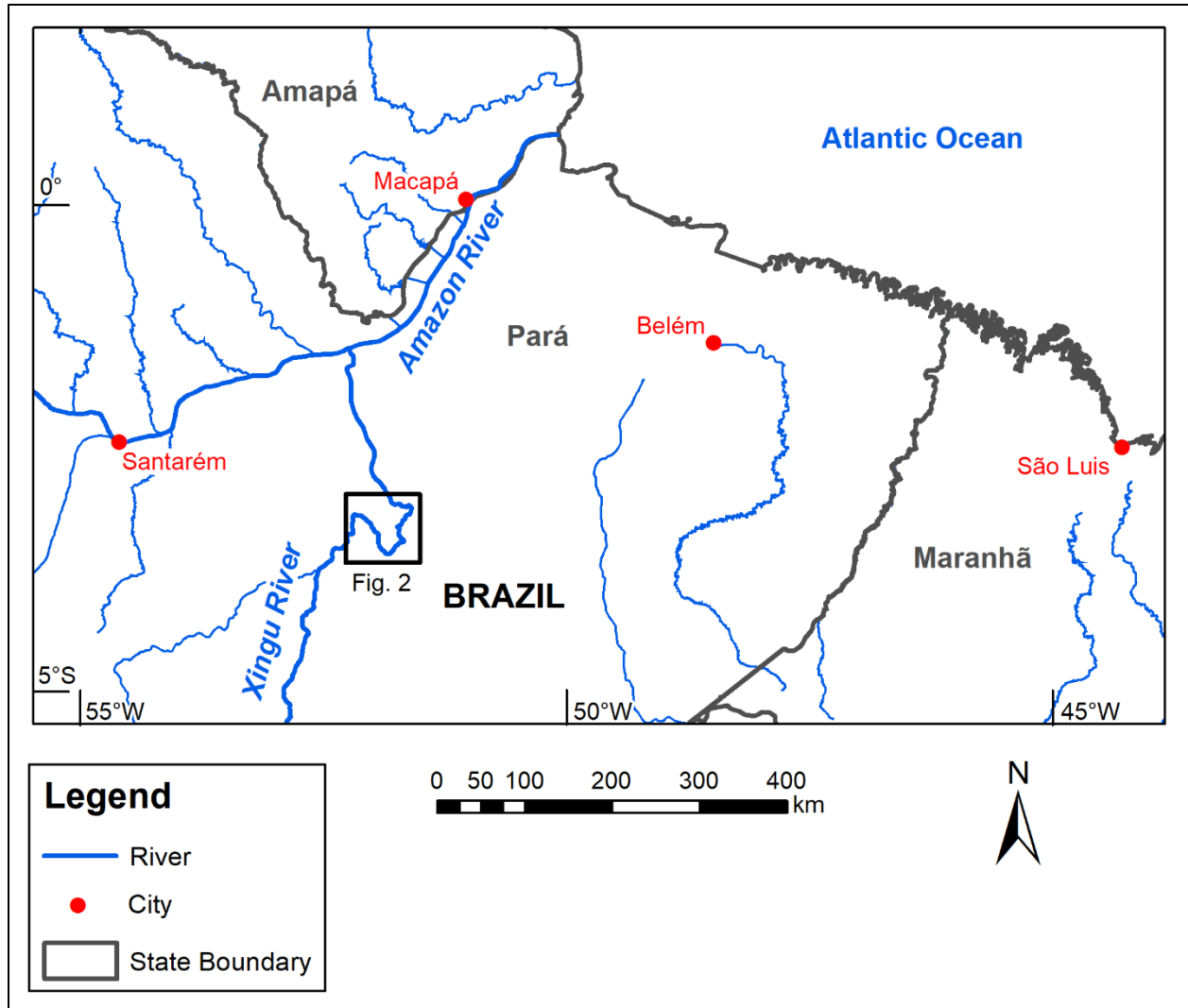
Figure 1. Belo Sun Mineração, a wholly-owned subsidiary of the Canadian company Belo Sun Mining, has proposed the Volta Grande Gold Project in the state of Pará in northern Brazil. The gold mine would be located on the banks of the Xingu River, which is a major tributary of the Amazon River.

A key environmental aspect of any mining project is the means of disposal of mine waste. For the Volta Grande Project, the largest category of waste would be the waste rock, or the rock that must be removed to reach the ore body. The waste rock from the Grota Seca open pit would be stored in a mound that would be 115 meters high and would contain 39.56 million cubic meters of rock by the end of the project. The waste rock from the Ouro Verde open pit would be stored in a mound that would be 140 meters high and would contain 20.08 million cubic meters of rock by the end of the project. The tailings are the crushed rock particles that remain after the gold is extracted from the ore. The tailings would be exported to a tailings deposit that would be confined by a 44-meter high tailings dam and which would store 35.43 million cubic meters of tailings and water by the end of the project. The tailings deposit would also store the spent cyanide leachate (cyanide solution remaining after extraction of the gold) following destruction of the cyanide (conversion of the cyanide into biologically harmless compounds of carbon and nitrogen) (Brandt Meio Ambiente, 2016a).

Figure 2. The proposed Volta Grande Gold Project would be located 15 kilometers south of the Belo Monte dam, which was completed in November 2019. A failure of the gold mine tailings dam would result in an initial runout of the tailings flood of 41.4 kilometers under the most-likely scenario, with significant impact on the Arara de Volta Grande do Xingu indigenous land. Under the worst-case scenario, the initial runout would be 98.1 kilometers along the Xingu River. Following the initial runout, normal fluvial processes would transport the tailings to the Amazon River and Atlantic Ocean (see Fig. 1). Most-likely and worst-case scenarios based on Larrauri and Lall (2018).

Figure 3. The infrastructure for the Volta Grande Project would include two open pits, two water storage ponds, two waste rock deposits, and a tailings deposit. Although the tailings deposit would be 1535 meters from the Xingu River, a tailings dam failure would probably result in the travel of tailings along the course of a stream channel for 2228 meters to the Xingu River. Based on an observed minimum tailings flood velocity of 20 kilometers per hour, the tailings would reach the Xingu River in less than 7 minutes. By contrast, Brandt Meio Ambiente (2016a) estimated that the tailings flood would reach the Xingu River in 97 minutes (corresponding to a tailings flood velocity of 1.4 kilometers per hour). Mine infrastructure and streams traced from Brandt Meio Ambiente (2016a, 2016c).

The objective of this report is to address the following question:
Do the Environmental Impact Study and related technical documents for the Volta Grande Gold Project provide adequate protection for people and the environment? This question can be subdivided into three questions:

1) Would the water consumption by the Volta Grande Project have a significant impact on the flow of the Xingu River?
2) Does the proposal include sufficient safeguards to prevent detrimental environmental impacts of cyanide use?
3) What would be the risk of failure of the tailings dam?

In terms of the last question, risk of failure is understood as a combination of (or as the product of) the probability of failure and the consequences of failure. Before discussing the methodology for addressing these questions, I will first review the subjects of mine tailings, tailings dams, and the use of cyanide for gold extraction. In light of these reviews, I will then review further details of the Volta Grande Project.

REVIEW OF TAILINGS AND TAILINGS DAMS

Tailings Dams and Water-Retention Dams

Although tailings dams and water-retention dams are 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 standard 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. Finally, 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. On the other hand, a tailings dam is expected to confine the toxic tailings in perpetuity, although normally the inspection and maintenance of the dam cease after the end of the mining project.

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.

It is most relevant that Brazil experienced 15 tailings dam failures from 1986 to 2019 (see Table 1; Fig. 4). Based on 769 tailings dams in Brazil as of February 2019 (Agência Nacional de Mineração [National Mining Agency], 2019a), the annual failure rate has been 0.06%. The calculated failure rate must be an underestimate because not all current tailings dams have been in existence since 1986. The annual tailings dam failure rate in Brazil is comparable to the global annual failure rate of 0.06-0.14% (Davies, 2002) and the annual failure rate in British Columbia of 0.17% (Independent Expert Engineering Investigation and Review Panel, 2015), but is significantly greater than the global annual failure rate of 0.01% for water-retention dams (Davies, 2002). It is alarming that the safety record of tailings dams in Brazil is not improving, but is becoming worse. In fact, the tailings dam failure rate in Brazil has been increasing exponentially with three failures occurring in 2019 alone (see Table 1 and Fig. 4).

Table 1. Tailings dam failures in Brazil, 1986-2019

Year	Mining Company	Municipality, State
2019[1]	VM Mineração e Construção	Nossa Senhora do Livramento, Mato Grosso
2019[1]	Metalmig Mineração Indústria	Machadindo d'Oeste, Rodônia
2019[1]	Vale SA	Brumadinho, Minas Gerais
2018[1]	Hydro Alunorte / Norsk Hydro ASA	Bacarena, Pará
2015[1]	Samarco Mineração SA	Mariana, Minas Gerais
2014[1]	Herculano Mineração	Itabirito, Minas Gerais
2012[2]	AngloGold Ashanti	Crixás, Goiá
2009[1]	Hydro Alunorte / Norsk Hydro ASA	Bacarena, Pará
2007[1]	Mineração Rio Pomba Cataguases	Miraí, Minas Gerais
2006[2]	Mineração Rio Pomba Cataguases	Miraí, Minas Gerais
2003[2]	Mineração Rio Pomba Cataguases	Miraí, Minas Gerais
2001[1]	Mineração Rio Verde	Nova Lima, Minas Gerais
1994[3]	AngloGold Ashanti	Crixás, Goiá
1986[1]	Itaminos Comercio de Minerios	Itabirito, Minas Gerais
1986[3]	Pico de São Luis	Rio Acima, Minas Gerais

[1]WISE Uranium Project (2020)
[2]World Mine Tailings Failures (2019)
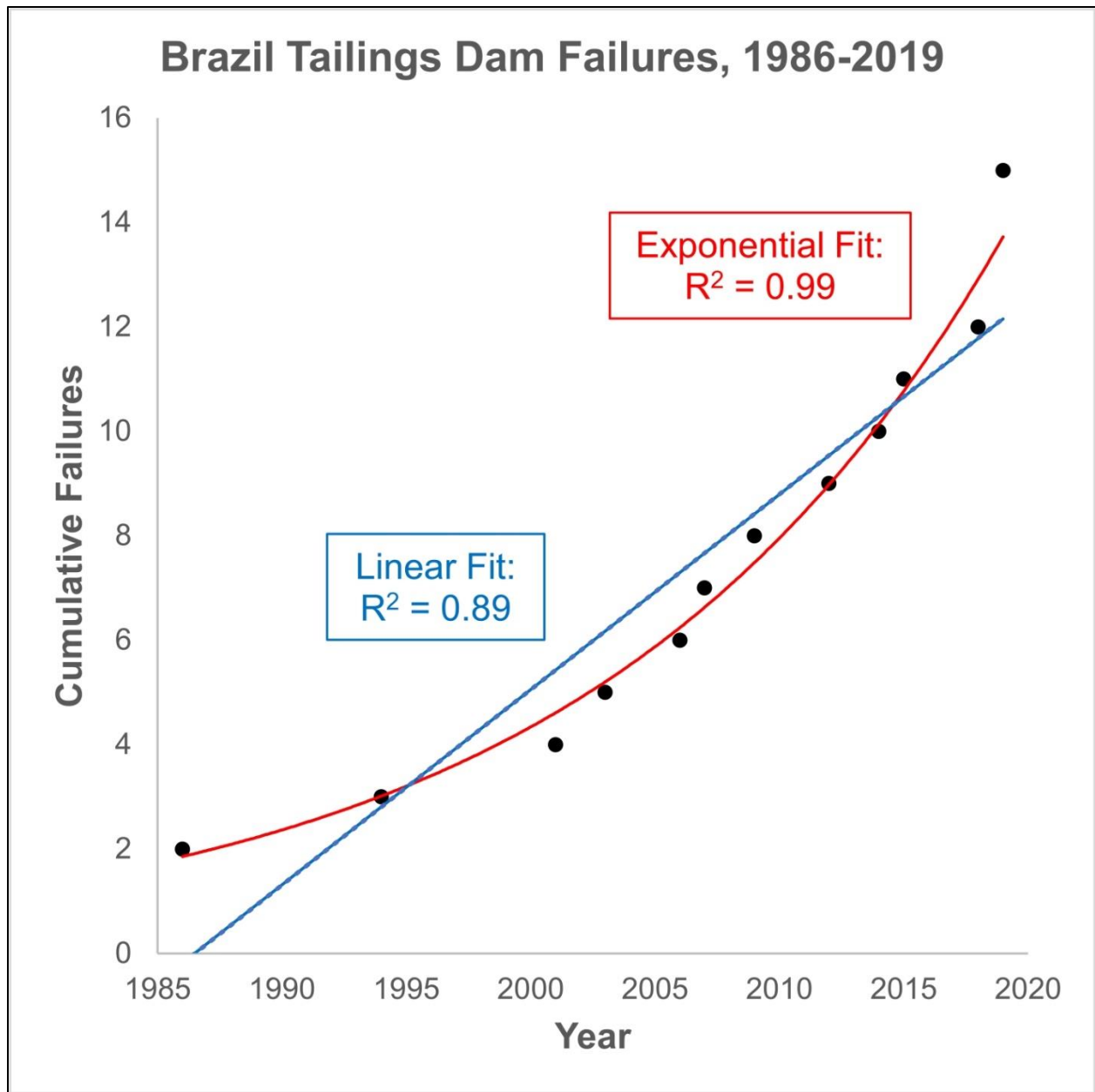[3]ICOLD and UNEP (2001)

Figure 4. Brazil experienced 15 tailings dam failures from 1986 to 2019 (see Table 1). Based on 769 tailings dams in Brazil as of February 2019 (Agência Nacional de Mineração, 2019a), the annual failure rate has been 0.06%. The calculated failure rate must be an underestimate because not all current tailings dams have been in existence since 1986. The annual tailings dam failure rate in Brazil is comparable to the global annual failure rate of 0.06-0.14% (Davies, 2002) and the annual failure rate in British Columbia of 0.17% (Independent Expert Engineering Investigation and Review Panel, 2015), but is significantly greater than the global annual failure rate of 0.01% for water-retention dams (Davies, 2002). The tailings dam failure rate in Brazil has been increasing exponentially with three failures occurring in 2019 alone (see Table 1).

Methods of Construction of Tailings Dams

All methods of construction of tailings dams are means of taking advantage of the very different physical properties of the two sizes of tailings, which are the sands (larger than 0.075 mm) and the slimes (smaller than 0.075 mm). These two sizes are separated by gravity in tailings

8

management facilities. Normally, a mixture of tailings and water is 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. 5). 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. It should be noted that the beach is essential for preventing the pond from reaching the crest of the dam.
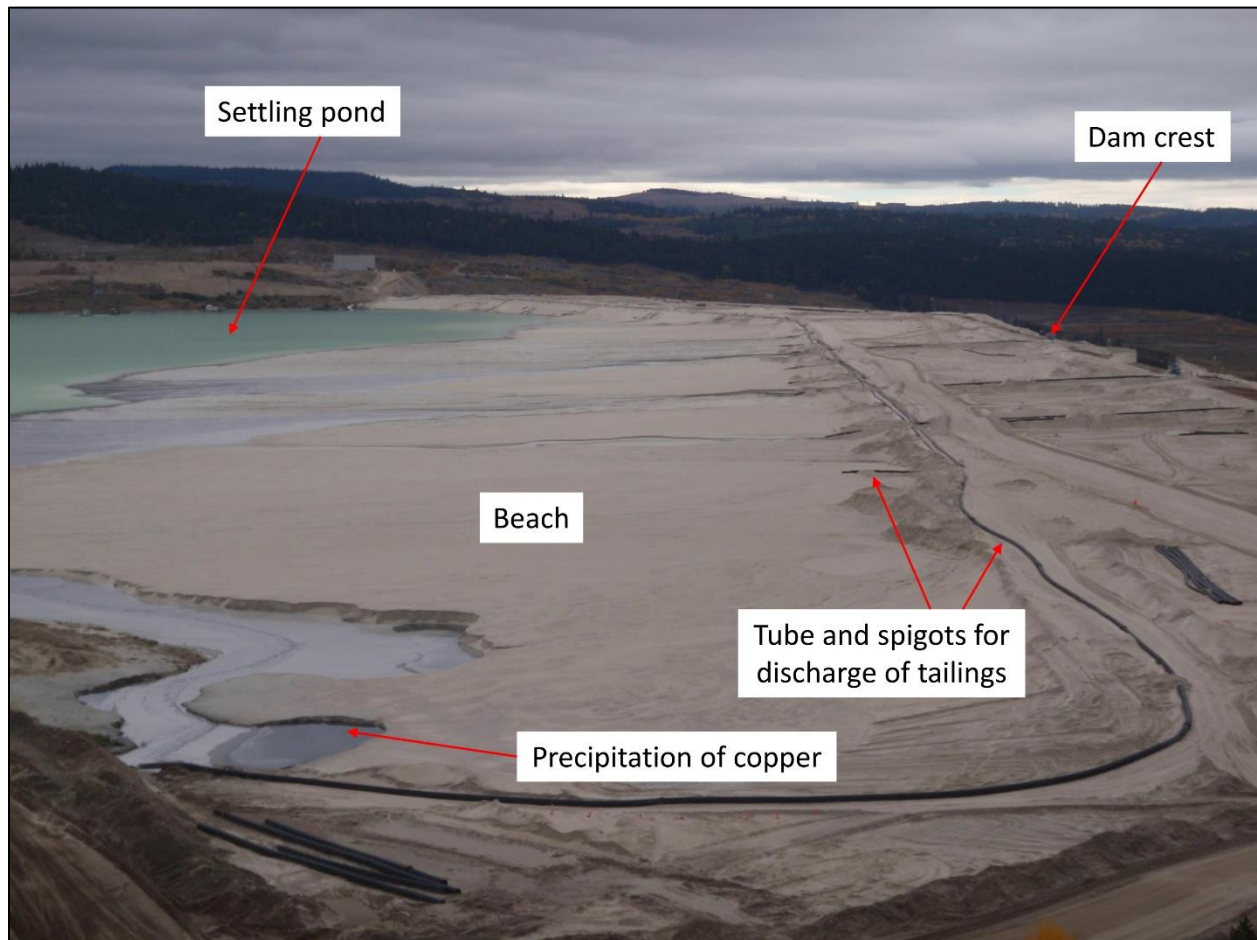

Figure 5. At the tailings storage facility of the Highland Valley Copper mine in British Columbia, wet tailings are discharged in the upstream direction from a tube and spigots along the crest of the dam. Larger particles (sands) are deposited near the dam to form a beach. Smaller particles (slimes) are transported farther from the dam to form a settling pond. The precipitation of copper in the tailings reservoir indicates the incomplete extraction of copper from the ore. Photo taken by the author on September 27, 2018.

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. 6a-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. 6a). The downstream construction method is the most expensive since it requires the most construction material (compare Figs. 6a and 6b). 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. 6a-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. 6c). 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.
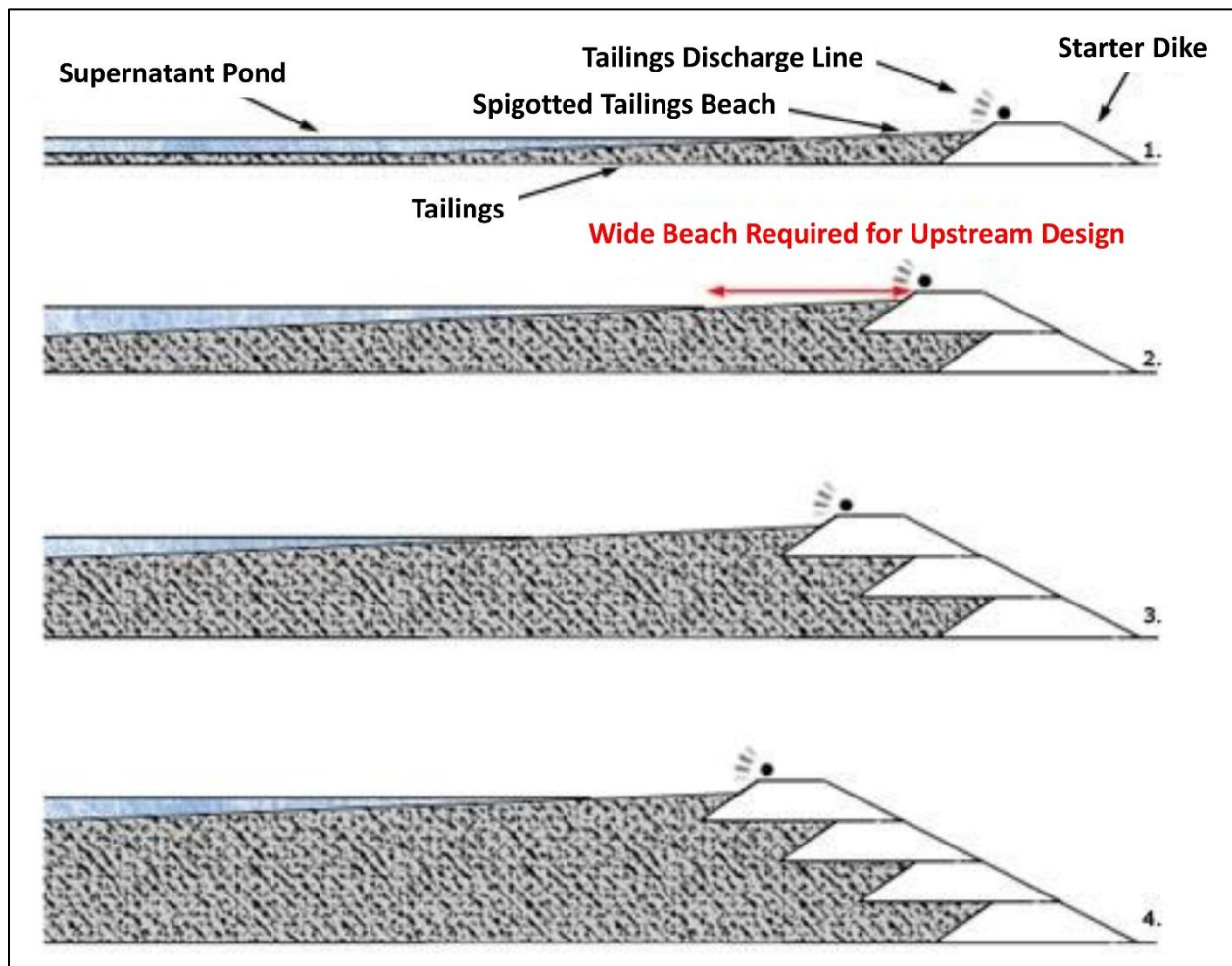

Figure 6a. In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. Dikes can be constructed with mine waste rock, natural soil, natural rock fill, or the coarser fraction of tailings (with proper compaction). The advantage of 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 flood failure 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 (2020).

Causes of Failure of Tailings Dams

The most common causes of failures of tailings dams are overtopping by floods, internal erosion, foundation failure, seismic liquefaction, and static liquefaction. 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. In terms of tailings dams, this emphasizes the importance of maintaining an adequate beach to keep the water away from the dam and keeping the water level below the level of the dam crest. For example, in the case of the tailings dam at the Highland Valley Copper Mine (see Fig. 5), the narrow beach (especially on the far side of the photo, where the beach is almost nonexistent) makes the dam susceptible to flood failure. This narrow beach has been the result of a shortage of sands in the tailings discharge.
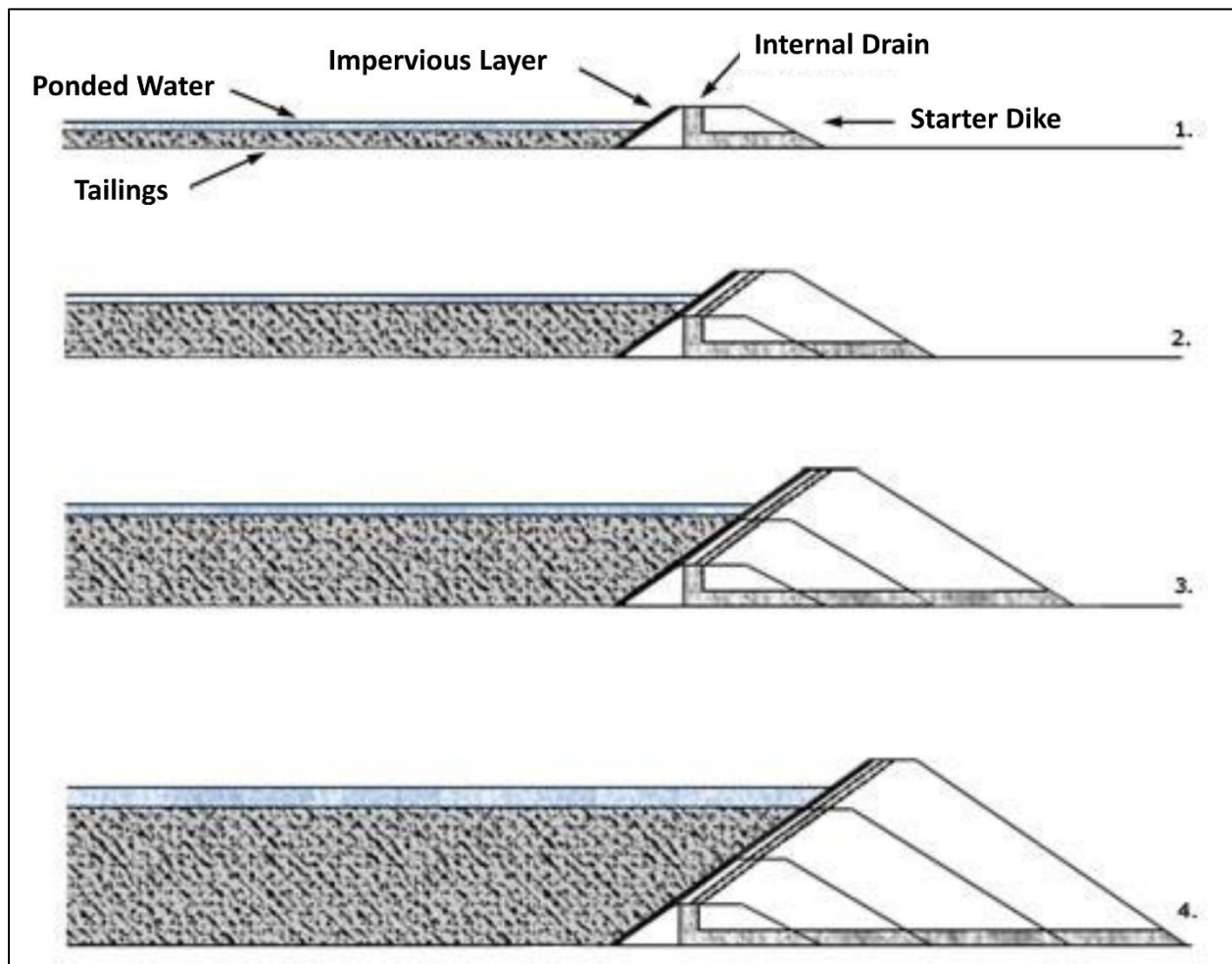

Figure 6b. In the downstream construction method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. Dikes can be constructed from mine waste rock, natural soil, natural rock fill, or the coarser fraction of tailings (with proper compaction). The resistance 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. 6a and 6b). Figure from TailPro Consulting (2020).

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 is prevented by reducing the water content of the tailings, lengthening the hydraulic flow paths (for example, by decreasing

11

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.
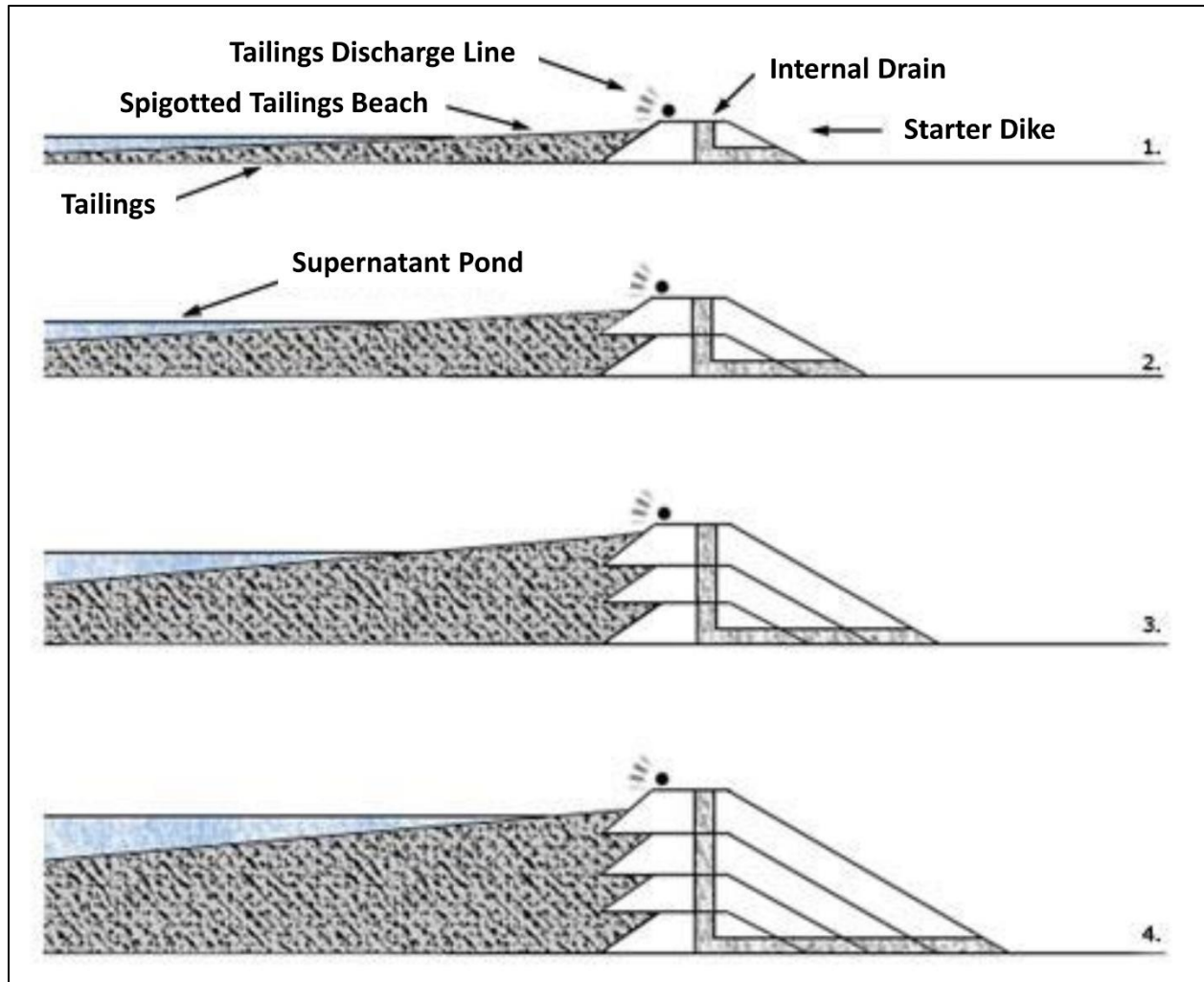

Figure 6c. In the centerline construction method, successive dikes are constructed by placing construction material on the beach and on the slope downstream of the previous dike. The central lines of the rises coincide as the dam is built upwards. Dikes can be constructed from mine waste rock, natural 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. 6a-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 avoid flooding the dam. Figure from TailPro Consulting (2020).

Liquefaction is the phenomenon in which a porous medium (usually sands) loses all strength and behaves as if it were a liquid. On the left-hand side of Fig. 7, although the solid particles are loosely packed and the pores are saturated, the particles touch each other, so that the load is supported by the particles (and partially by the water). On the right-hand side of Fig. 7, following an increase in load or a disturbance (such as an earthquake), the solids could suddenly consolidate to a more densely-packed state. If the water cannot escape (due to low permeability or the speed of the disturbance), the water is compressed and the water pressure increases, so that

the particles no longer touch each other. In this case, the water supports the entire load, so that the mass of particles and water behaves like a liquid. This phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles.

Figure 7. In the diagram on the left, although the solid particles are loosely packed and the pores are saturated, the particles touch each other, so that the load is supported by the particles (and partially by the water). In the diagram on the right, following an increase in load or a disturbance (such as an earthquake), the solids consolidate to a more densely-packed state. If the water cannot escape (due to low permeability or the speed of the disturbance), the water is compressed and the water pressure increases, so that the particles no longer touch each other. In this case, the water supports the entire load, so that the mass of particles and water behaves like a liquid. This phenomenon of liquefaction is pro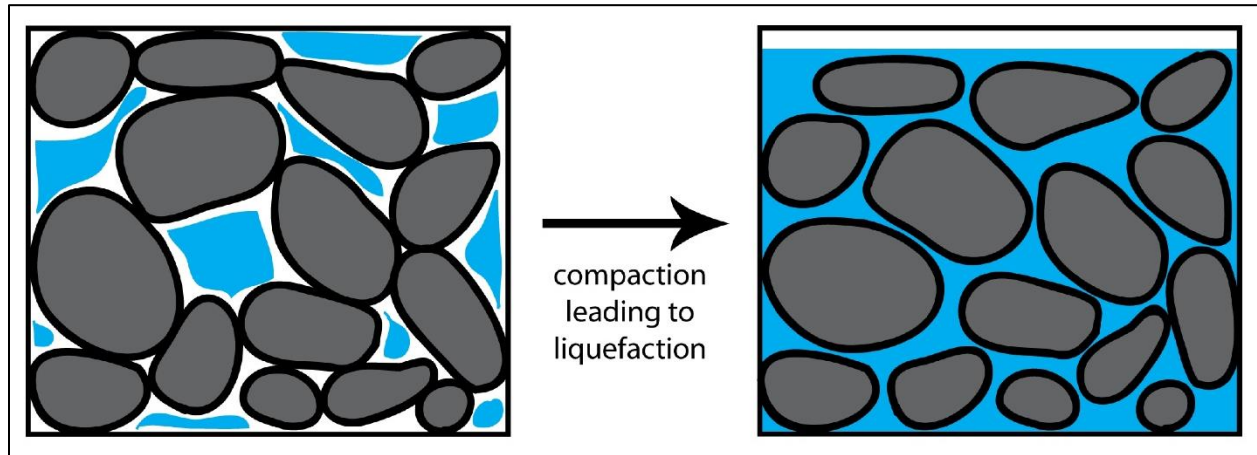moted by saturated pores and loosely-packed particles. Tailing deposits are especially susceptible to liquefaction because the tailings are very loosely-packed due to the hydraulic discharge into the reservoir without compaction (see Fig. 5). Figure from DoITPoMS (2019).

A distinction is usually made between seismic liquefaction and static liquefaction. During seismic activity, the cyclic stresses can induce a sudden consolidation of the tailings. Liquefaction due to all other possible triggers is called static liquefaction. These triggers could include an increase in the load of tailings (especially when tailings are added so fast that the underlying tailings do not have time to consolidate), heavy rainfall, or seismic-like disturbances, such as blasting. Tailing deposits are especially susceptible to liquefaction because the tailings are very loosely-packed due to the hydraulic discharge into the reservoir without compaction (see Fig. 5). The key to avoiding liquefaction is to keep the water table (the boundary separating the overlying unsaturated pores and the underlying pores saturated with water) within the tailings reservoir as low as possible. Even with a low water table, it is still important to keep the water content low in the region above the water table because liquefaction can still occur even if the pores are only 80% saturated prior to the sudden consolidation. Failure of the foundation (the earth beneath the tailings management facility or beneath the dam itself) is also usually 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.

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 more expensive construction methods are also less 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. 6a). 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. For this reason, the upstream construction method is illegal in Chile (Ministerio de Minería [Ministry of Mining], 2007), Ecuador (Valencia, 2019) and Peru (Sistema Nacional de Información Ambiental [National System of Environmental Information], 2014) due to their high potential for strong earthquakes. The upstream construction method is even banned in Brazil (Agência Nacional de Mineração [National Mining Agency], 2019b; Assembleia Legislativa de Minas Gerais [Legislative Assembly of Minas Gerais], 2019), and effectively banned in the province of Ontario, Canada (MacDonald et al., 2019), where the potential for large earthquakes is much lower. 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. 6c). 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. 6b). Of course, proper design and construction are still needed to prevent liquefaction of the dam itself even when the downstream method is used.

Reduction of Water Content of Stored Tailings

By this point, 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 (overtopping by floods, internal erosion, foundation failure, seismic or static liquefaction) 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 water table can be lowered with appropriate impermeable layers and internal drainage systems (see Figs. 6b-c). However, it is most important to address the root cause of excessive water, which is the excessive export of water to the tailings management facility.

In conventional tailings management, all of the water that is mixed with the crushed ore in the ore processing plant is shipped to the tailings pond, so that the mixture of water and tailings has a solids content in the range 20-40% by weight, or sometimes as high as 60%. A safer technology is to convert the tailings into a high-density thickened slurry or a paste, with a solids content of 60-75% by weight, before shipment to the tailings pond. The safest technology at the present time is to filter the tailings to a solids content greater than 80%, so that the tailings behave like a moist soil, as opposed to a slurry or a paste (Klohn Crippen Berger, 2017). The additional advantage of filtering is that it is possible to compact the tailings prior to storage, which further reduces the likelihood of liquefaction (see Fig. 7). At the present time, filtered tailings technology should be regarded as the Best Available Technology (BAT) (Independent Expert Engineering Investigation and Review Panel, 2015).

Design Earthquakes

Any tailings dam must be designed to resist a particular flood and a particular earthquake, called the design flood and the design earthquake. Without a knowledge of the design flood and design earthquake, there is no basis for determining the minimum width of the tailings beach, the maximum slope of the outer embankment, or any other aspect of a tailings management facility.

The design earthquake is really a design seismic acceleration, which depends on the magnitude of the design earthquake, the distance from the fault at which the earthquake is expected to occur, and the nature of the material under the dam. Typically, the design flood and design earthquake depend on the hazard potential or the consequences of the failure. In this subsection, three widely-recognized guidelines for determining design earthquakes will be considered, which are the guidelines of the (U.S.) Federal Emergency Management Agency (FEMA, 2005, 2013), the U.S. Army Corps of Engineers (USACE, 2016), and the Canadian Dam Association (2013). Finally, the current regulations in Brazil will be considered. This subsection will emphasize design earthquakes as opposed to design floods, as most relevant to an evaluation of the Volta Grande Project.

The Federal Emergency Management Agency classifies dams in three categories according to the hazard potential (FEMA, 2013). High Hazard Potential means "probable loss of life due to dam failure or misoperation." It is clarified that "probable loss of life" refers to "one or more expected fatalities" and that "economic loss, environmental damage or disruption of lifeline facilities may also be probable but are not necessary for this classification." Significant Hazard Potential means "no probable loss of human life but can cause economic loss, environmental damage, or disruption of lifeline facilities due to dam failure or misoperation." Low Hazard Potential means "no probable loss of human life and low economic and/or environmental losses due to dam failure or misoperation."

Each of the hazard potentials corresponds to a design earthquake. According to the Federal Emergency Management Agency, the Maximum Credible Earthquake (MCE), is "the largest earthquake magnitude that could occur along a recognized fault or within a particular seismotectonic province or source area under the current tectonic framework" (FEMA, 2005). Furthermore, for dams with High Hazard Potential, "the MDE [Maximum Design Earthquake] usually is equated with the controlling MCE." However, "where the failure of the dam presents no hazard to life, a lesser earthquake may be justified, provided there are cost benefits and the risk of property damage is acceptable" (FEMA, 2005). Similar language is used by the U.S. Army Corps of Engineers in stating, "for critical features, the MDE is the same as the MCE" (USACE, 2016) and has emphasized that "there is no return period for the MCE" (USACE, 2016), meaning that the MCE has no specified annual probability of occurrence. On the other hand, in the context of discussing criteria for determining the MCE at a particular location, FEMA (2005) states, "For high-hazard potential dams, movement of faults within the range of 35,000 to 100,000 years BP is considered recent enough to warrant an 'active' or 'capable' classification." In other words, the MCE can be as rare as a 100,000-year earthquake, with a corresponding annual exceedance probability of 0.001%. FEMA (2005) continues, "However, for low or significant-hazard dams, the MDE may be determined based on faults active in Holocene time." Since the Holocene Epoch has nominally lasted for the past 10,000 years, the design earthquake for a dam with Low or Significant Hazard Potential would be equivalent to a 10,000-year earthquake (annual exceedance probability of 0.01%).

The guidelines of the Canadian Dam Association (2013) include five dam classes, classified according to the consequences of failure. Risk to any permanent population places a dam in the three highest-consequence categories, in which the high-consequence, very high-consequence and extreme-consequence categories correspond to expected deaths of ten or less, 100 or less, and more than 100, respectively. The guidelines consider earthquake design criteria based on both a risk-informed approach and a traditional, standards-based approach. According to the risk-informed approach, the minimum annual exceedance probability of the design

earthquake in the very high- or extreme-consequence categories should be 1/10,000 (corresponding to a return period of 10,000 years). According to the traditional, standards-based approach, for a dam in the very high-consequence category, the design earthquake should be halfway between the 2,475-year earthquake and either the 10,000-year earthquake or the MCE. For a dam in the extreme-consequence category, the design earthquake should be the 10,000-year earthquake or the MCE.

The current Brazilian tailings dam regulations are specified in Portaria [Ordinance] No. 70.389 (Agência Nacional de Mineração, 2017). This ordinance in turn requires the "*análise da estabilidade da Barragem de Mineração a qual concluirá pela Declaração de Condição de Estabilidade tendo por base os índices de fator de segurança descritos na Norma Brasileira ABNT NBR 13.028 ou Norma que venha a sucedê-la, fazendo uso das boas práticas da engenharia* [analysis of the stability of the Mining Dam, which will conclude by the Declaration of Stability Condition, based on the factor of safety values described in the Brazilian Standard ABNT NBR 13.028 or any Standard that will succeed it, taking into account best engineering practices] (Agência Nacional de Mineração, 2017). The factor of safety is the lowest value of the ratio of the shear resistance to the shear stress, considered over all possible failure surfaces within the tailings management facility (Canadian Dam Association, 2013). The factor of safety can be calculated either under static conditions (zero seismic acceleration) or under the seismic acceleration of a design earthquake. ABNT NBR 13.028 then states, "*Os estudos sísmicos devem avaliar o potencial de sismicidade na área de implantação da barragem, com base em bibliografia, incluindo normas existentes e registros. Recomenda-se, para as etapas iniciais de estudo, a utilização do critério sugerido pela Canadian Dam Association (CDA), que indica a adoção da aceleração da gravidade resultante do Sismo Máximo Provável (MCE – Maximum Credible Earthquake) para análise pseudoestáticas [cálculo do fator de segurança sob o sismo de desenho]*" [Seismic studies should assess the potential for seismicity in the area where the dam is located, based on a bibliography, including existing standards and records. It is recommended, for the initial stages of the study, the use of the criterion suggested by the Canadian Dam Association (CDA), which indicates the adoption of the acceleration resulting from the Maximum Credible Earthquake (MCE) for the pseudostatic analysis [calculation of the safety factor under the design earthquake] (ABNT, 2017). On the above basis, the requirement of design for the MCE, regardless of the consequences of tailings dam failure, gives Brazil the most rigorous seismic design criterion for tailings dams in the world. In a similar way, the Australian National Committee on Large Dams states, "When considering the MDE, the concept of Maximum Credible Earthquake (MCE) is often used…For closure the MCE should be used for design but taking into account expected long term properties of the tailings" (ANCOLD, 2012).

REVIEW OF USE OF CYANIDE FOR GOLD ORE BENEFICIATION

A cyanide solution acts as a lixiviant for gold, meaning that it selectively extracts the gold from the crushed particles of gold ore. In particular, cyanide dissolved in water reacts with solid gold to form a dissolved gold-cyanide complex. The solution with the gold-cyanide complex is called the pregnant solution. When the pregnant solution is passed over or mixed with activated carbon (charcoal), the activated carbon removes the gold from the gold-cyanide complex in the pregnant solution, after which further processing separates the gold and carbon to form a pure gold. Some of the spent solution (cyanide solution after the gold removal) is then recycled through the ore processing operation after replacing any lost cyanide. The remainder of

the spent cyanide solution is shipped to the tailings pond along with the mine tailings. Unless the tailings have been filtered or substantially thickened, the greater part of the material that is shipped to the tailings pond is the spent cyanide solution.

Cyanide is highly toxic to aquatic organisms. A failure of the tailings dam at the Omai gold mine in Guyana in 1995 released 4.2 million cubic meters of cyanide-contaminated water into the Omai River, fortunately, with only minor fish kill (ICOLD and UNEP, 2001). However, the failure of a tailings dam at the Aurul S.A. gold mine near Baia Mare, Romania, in 2000 released 100,000 cubic meters of cyanide-contaminated water. The cyanide was transported through the Somes and Tisza Rivers to the Danube River and finally into the Black Sea, resulting in significant fish kill and destruction of aquatic species (ICOLD and UNEP, 2001). The impacts of cyanide tend to be short-term because dissolved cyanide rapidly oxidizes to form carbon dioxide and ammonia. For that reason, it is preferable to oxidize the cyanide before the tailings and spent cyanide solution are exported to the tailings pond.

The long-term impacts of cyanide use tend to result from the by-products of gold ore processing. In particular, the cyanide solution also extracts mercury from the crushed ore. Mercury is not removed by the activated carbon so that it remains in the spent cyanide solution, even after oxidation of the solution. In addition, the use of a cyanide solution requires highly alkaline water (pH about 10.5) to keep the dissolved cyanide from converting into the highly toxic gas, hydrogen cyanide. This alkaline solution has the result of dissolving arsenic and antinomy from the gold ore, which will also remain in the spent cyanide solution even after treatment with activated carbon and oxidation. Further information about cyanide use is available on the website of the International Cyanide Management Institute (2020).

DESIGN OF THE VOLTA GRANDE GOLD PROJECT

The tailings dam for the Volta Grande Project would be constructed in two stages using the downstream construction method (see Figs. 6b and 8). The starter dike would be constructed out of compacted soil from the project site to a height of 26.5 meters. The final dike would be constructed out of compacted soil on the upstream side and mine waste rock on the downstream side to a final height of 44 meters (see Fig. 8). Before export to the tailings pond, the cyanide would be destroyed using sulfur dioxide and the tailings would be thickened to a solids content of 53% by weight. The tailings dam would have zero downstream discharge in that all seepage from the dam would be pumped back into the tailings pond (Brandt Meio Ambiente, 2016a; VOGBR, 2016a).

Since water is always recycled throughout a mining operation to some extent, water consumption can be much less than water use. Water consumption refers to water that must be replaced by withdrawals from surface water or groundwater resources. Water consumption is also called the "blue water footprint" and includes water lost by evaporation, water that is stored within the pores of the tailings, and any water that is not returned to the same catchment area from which it was withdrawn (Northey and Haque, 2013). In the case of the Volta Grande Project, Brandt Meio Ambiente (2016a) predicted a water usage of 473.1 cubic meters of water per hour, including the recycling of 211.2 cubic meters of water per hour from the tailings pond and the withdrawal of 261.9 cubic meters of water per hour from surface water (corresponding to the consumption of water). This most recent prediction of water consumption is much greater than the prediction from the previous year (Chubb et al., 2015) of consuming 80 cubic meters of water per hour during a Phase I of operation (3.5 million metric tons of ore per year with average

grade of 1.56 grams of gold per metric ton of ore) and 130 cubic meters of water per hour during a Phase II of operation (7 million metric tons of ore per year with average grade of 0.97 grams of gold per metric ton of ore). Further details regarding the design of the Volta Grande Project will be provided when responding to specific questions in the Results section.
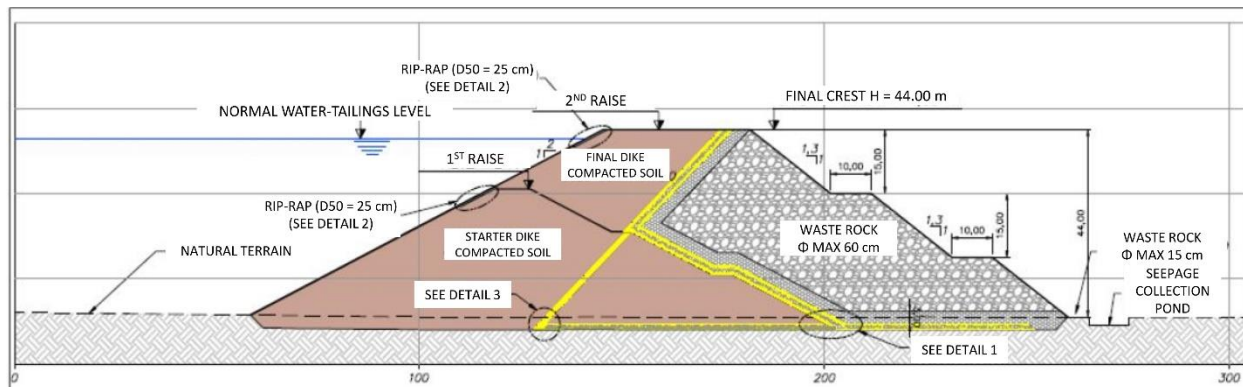

Figure 8. The tailings dam for the proposed Volta Grande Gold Project would be constructed in two raises using the downstream method (see Fig. 6b), with a final height of 44 meters. The starter dike would be constructed out of compacted soil, while the final dike would be constructed out of compacted soil on the upstream side and mine waste rock on the downstream side. Although the downstream method is the safest of the three most common construction methods, the additional security probably does not counterbalance the additional risk created by the excessive amount of water that would be stored behind the dam. The yellow lines indicate the internal drainage system. Figure from VOGBR (2016a) overlain with English labels.

METHODOLOGY

In light of the preceding reviews of tailings, tailings dams and the use of cyanide, the three questions stated earlier can be further subdivided into a set of six questions:
1) Is the predicted water consumption of the Volta Grande Project consistent with trends in the gold mining industry and would it be a significant fraction of the flow of the Xingu River?
2) Is the proposed reduction in the water content of the stored tailings from the Volta Grande Project consistent with trends in and guidelines for the mining industry?
3) Are the analysis of local and regional seismicity and the choice of a design earthquake consistent with internationally-recognized guidelines and Brazilian tailings dam regulations?
4) Does the proposal for the Volta Grande Project provide adequate environmental protection from the typical toxic by-products of cyanide use (arsenic, antimony, mercury)?
5) Does the proposal for the Volta Grande Project adequately and correctly predict the consequences of tailings dam failure?
6) Does the proposal for the Volta Grande Project include an adequate plan for safe closure of the tailings dam after the 12 years of the mining operation?

An assessment of the annual probability of failure of the tailings dam will be considered in the Discussion section.

The six questions were largely addressed by comparison of the 2015 Feasibility Study (Chubb et al., 2015) and the documents of the 2016 Environmental Impact Study (EIS) with current trends in and guidelines and regulations for the mining industry, with emphasis on gold mining and on the mining industry in Brazil. The key sections of the 2016 EIS were Brandt Meio Ambiente (2016a-c) and VOGBR (2016a-b). Not all sections of the 2016 EIS were available to the author. However, the missing sections seemed to be only detailed analyses, for which the

18

summaries and conclusions could be found in sections that were available. The most recent versions of the proposal for the Volta Grande Project are the two Indigenous Component Studies that consider the possible impacts of the gold project on the indigenous lands of the Paquiçamba and the Arara da Volta Grande do Xingu (see Fig, 3) (JGP Consultoria e Participações [JGP Consulting and Submissions], 2020a-b). These documents include only a summary of the technical information available in the 2016 EIS with no changes or additional details.

The fifth question regarding the consequences of tailings dam failure was addressed by comparing the conclusions of Brandt Meio Ambiente (2016a) with the most recent statistical model of past tailings dam failures (Larrauri and Lall, 2018). The statistical model predicts the initial runout of tailings following dam failure. The initial runout is the distance covered by the tailings due to the release of gravitational potential energy as the tailings fall out of the tailings pond. After the cessation of the initial runout, normal colluvial or fluvial processes could transport the tailings downslope or downstream indefinitely until the tailings reach the ocean or a closed basin. When the initial runout reaches a major river, as would happen in the failure of the tailings dam of the Volta Grande Project, it can be difficult to separate the initial runout from the subsequent normal fluvial processes. For example, the failure of the tailings dam at the Samarco mine (see Table 1) spilled tailings into the Doce River, so that the initial runout extended 637 kilometers to the Atlantic Ocean (Larrauri and Lall, 2018).

According to (Larrauri and Lall, 2018), the best predictor of the initial runout of released tailings is the dam factor H_f, defined as

$$H_f = H \left(\frac{V_F}{V_T} \right) V_F \tag{1}$$

where H is the height of the dam (meters), V_T is the total volume of confined tailings and water (millions of cubic meters), and V_F is the volume of the spill (millions of cubic meters). The most-likely predictions for the volume of the spill and the initial runout D_{max} (kilometers) are then

$$V_F = 0.332 \times V_T^{0.95} \tag{2}$$

$$D_{max} = 3.04 \times H_f^{0.545} \tag{3}$$

It should be noted that Eqs. (2)-(3) express the most-likely consequences of dam failure. In particular, the most-likely consequence is that dam failure will result in the release of about one-third of the stored tailings (see Eq. (2)). However, the worst-case scenario is that dam failure will result in the release of 100% of the stored tailings, for which there are examples (Larrauri and Lall, 2018). Therefore, the worst-case runout ($V_F = V_T$) should be calculated using Eq. (3) with

$$H_f = HV_F \tag{4}$$

Additional discussion of mining industry trends and guidelines that were used for comparison with the Volta Grande Project will be presented in the Results section.

RESULTS

Adequacy of Prediction of Water Consumption

Water consumption trends in the gold mining industry can be based upon either water consumption per unit ore production (Mudd, 2007a-b; Gunson, 2013; Department of Water and Sanitation, 2016) or per unit gold production (Mudd, 2007a-b, 2010; Norgate and Haque, 2012; Gunson, 2013). Estimates based on ore production have ranged from 0.745 to 2.56 cubic meters of water per metric ton of ore (see Table 2), with the lower value (Gunson, 2013) being the most recent and comprehensive (based on global gold mines). Estimates based on gold production have ranged from 259,290 to 691,000 cubic meters of water per metric ton of gold (see Table 2), with the most recent and comprehensive being 400,000 cubic meters of water per metric ton of gold (Gunson, 2013). The literature on water and other resource consumption trends has been reviewed by Tost et al. (2018).

Table 2. Average water consumption by gold mines and estimates for Volta Grande Project

Source	Based on Ore Production (m³ water / metric ton ore)	Based on Gold Production (m³ water / metric ton gold)
Study		
Mudd (2007a)	1.42	691,000
Mudd (2007b)	0.88	325,000
Mudd (2010)		634,900
Norgate and Haque (2012)		259,290
Norgate and Haque (2012)[1]		288,140
Gunson (2013)	0.745	400,000
DWS[2] (2016)	2.56	
Volta Grande Project		
2016 EIS	0.655[3]	445,920[3,4]
2015 Phase I	0.200[5]	128,350[5,6]
2015 Phase II	0.163[7]	167,720[7,8]

[1]Norgate and Haque (2012) used two different methods.
[2]Department of Water and Sanitation (South Africa)
[3]Water consumption = 261.9 m³/hr, ore production = 3.5 Mt/a (Brandt Meio Ambiente, 2016a)
[4]Grade = 1.47 g Au/ton (Brandt Meio Ambiente, 2016a)
[5]Water consumption = 80 m³/hr, ore production = 3.5 Mt/a (Chubb et al., 2015)
[6]Grade = 1.56 g Au/ton (Chubb et al., 2015)
[7]Water consumption = 130 m³/hr, ore production = 7 Mt/a (Chubb et al., 2015)
[8]Grade = 0.97 g Au/ton (Chubb et al., 2015)

Based upon the predicted water consumption (261.9 cubic meters of water per hour), ore production rate (3.5 million metric tons per year) and grade (1.47 grams of gold per metric ton) for the Volta Grande Project, the per unit water consumption would be 0.655 cubic meters of water per metric ton of ore and 445,920 cubic meters of water per metric ton of gold (see Table 2). Although no document has presented a detailed water budget, the above predictions are fully consistent with gold mining industry trends (see Table 2). On the other hand, the predicted hourly water consumption, ore production rate and average grade of the earlier Feasibility Report (Chubb et al., 2015) would have predicted unit water consumptions of 0.200 cubic meters of

water per metric ton of ore and 128,350 cubic meters of water per metric ton of gold for Phase I, and 0.163 cubic meters of water per metric ton of ore and 167,720 cubic meters of water per metric ton of gold for Phase II (see Table 2). The earlier predictions would have been much less than is typical for the gold mining industry and were not accompanied by any explanation as to how such high water efficiency would be achieved. Thus, a more realistic understanding of water efficiency seems to have occurred between the 2015 Feasibility Study (Chubb et al., 2015) and the 2016 EIS (Brandt Meio Ambiente, 2016a).
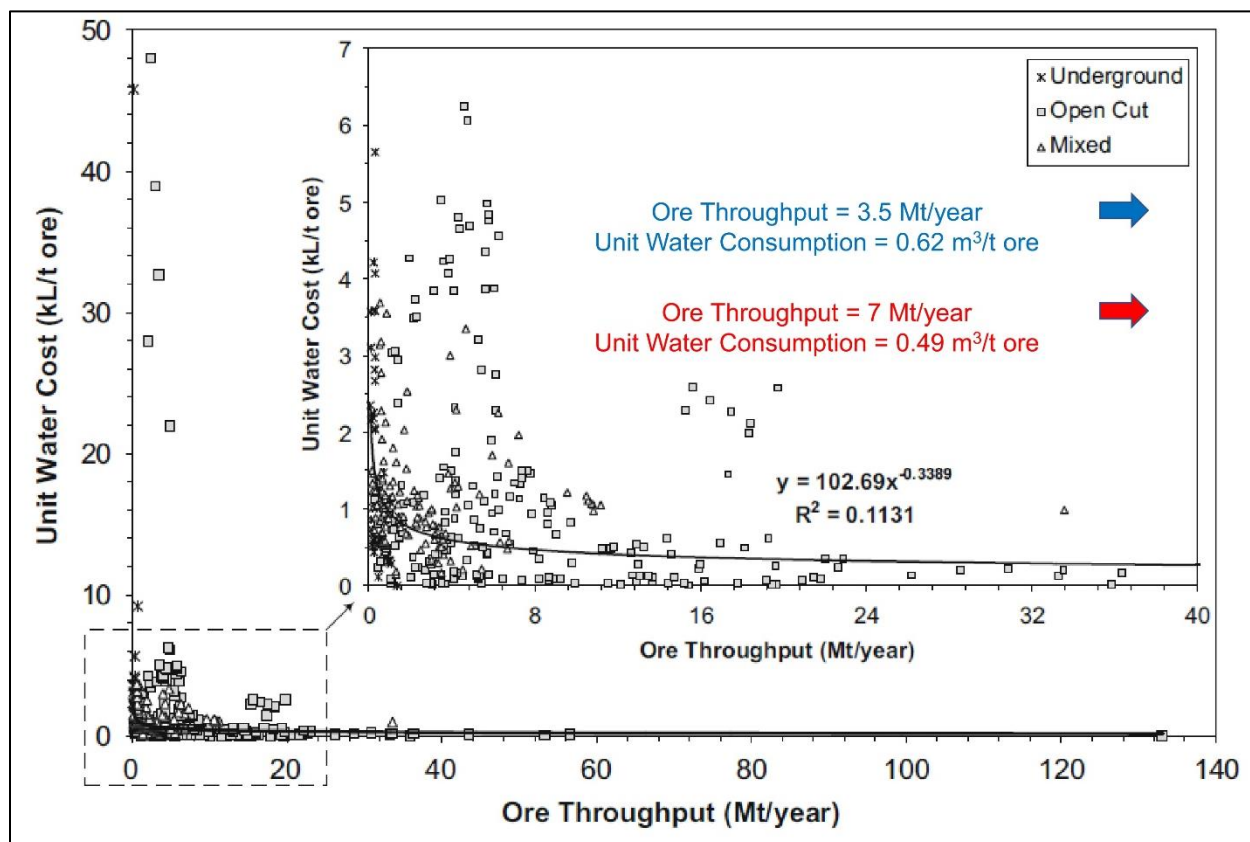

Figure 9. Brandt Meio Ambiente (2016a) estimated the water consumption of the proposed Volta Grande Gold Project to be 261.9 cubic meters per hour for an ore production rate of 3.5 million metric tons per year, corresponding to 0.655 cubic meters of water per metric ton of ore (see Table 2). The estimate is consistent with the best-fit curve for global gold mines (Mudd, 2010), which predicts unit water consumption of 0.62 cubic meters of water per metric ton of ore for the same ore production rate. By contrast, an earlier estimate for the proposed gold mine of 0.163 cubic meters of water per metric ton of ore for an annual ore production rate of 7 million metric tons (see Table 2; Chubb et al., 2015) would be much lower than the prediction based on global gold mines (0.49 cubic meters of water per metric ton of ore). Figure modified from Mudd (2010).

The predicted water consumption of the Volta Grande Project can also be compared with typical water consumption rates of gold mines as a function of ore throughput (Mudd, 2010). Although there is considerable scatter in the global data, marked improvements in water efficiency seem to occur for ore throughputs greater than about 3 million metric tons per year (see Fig. 9). For the ore production rate of the Volta Grande Project (3.5 million metric tons per year), the best-fit power-law curve to the global data predicts water consumption of 0.62 cubic meters of water per metric ton of ore (see Fig. 9), which is remarkably similar to the prediction for the Volta Grande Project (0.655 cubic meters of water per metric ton of ore). For the ore

production rate of the Phase II of the 2015 Feasibility Study (Chubb et al., 2015), the best-fit curve predicts water consumption of 0.49 cubic meters of water per metric ton of ore, which is again much greater than the earlier prediction. In summary, the predicted water consumption of the Volta Grande Project does not require any innovation in water efficiency.

The water consumption of the Volta Grande Project should also be compared with the flow rate of the Xingu River, since the gold mine would be consuming water that would have contributed to the streamflow. According to its agreement with the Brazilian government, Norte Energia, the company that operates the Belo Monte dam, is obligated to supply 700 cubic meters per second to the Xingu River below the dam (see Fig. 2; Higgins, 2020). The water consumption of the Volta Grande Project (261.9 cubic meters per hour or 0.07 cubic meters per second) would be only 0.01% of even the minimum flow of the Xingu River. Therefore, the Volta Grande Project would have an insignificant impact on the flow of the Xingu River.
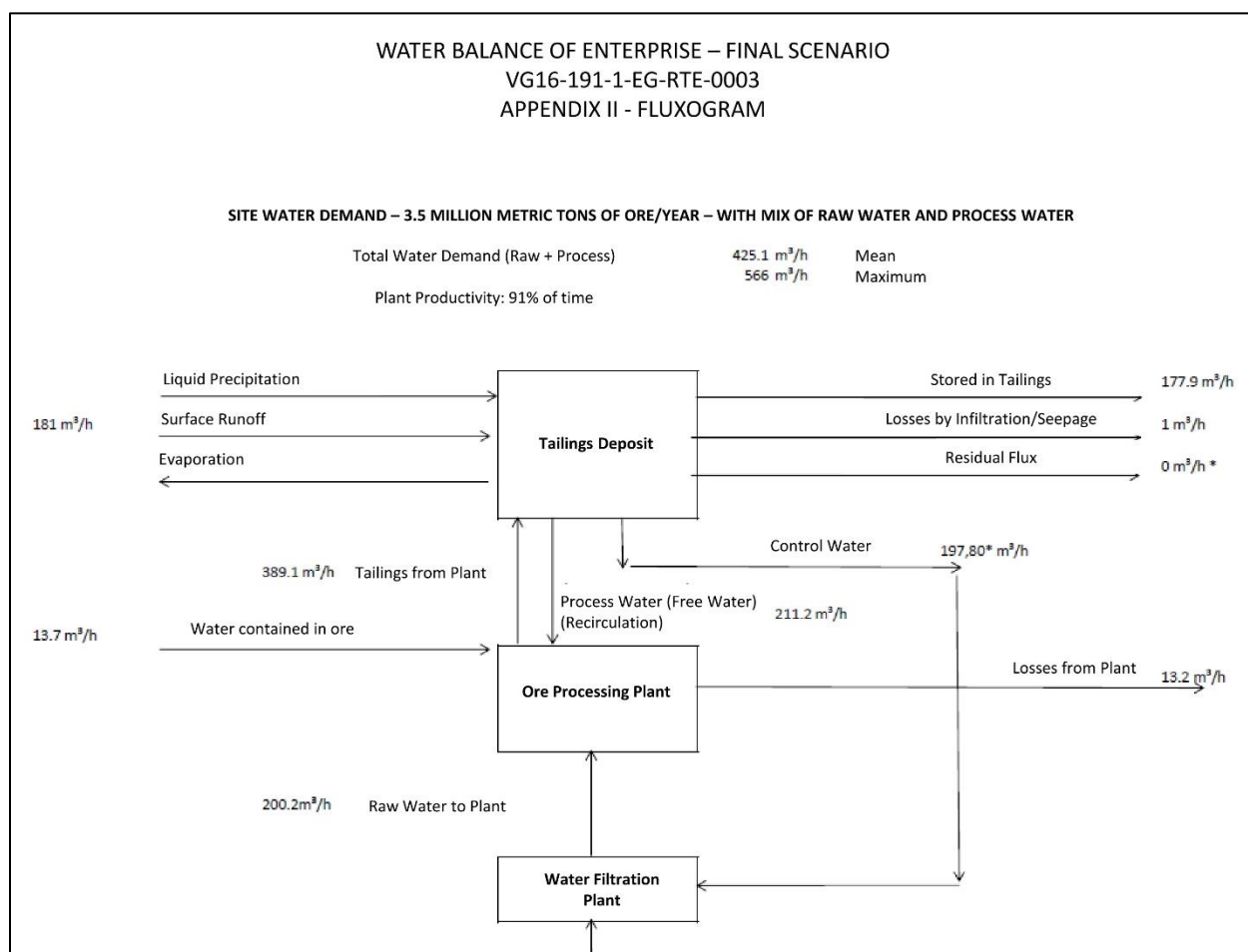

WATER BALANCE OF ENTERPRISE – FINAL SCENARIO
VG16-191-1-EG-RTE-0003
APPENDIX II - FLUXOGRAM

SITE WATER DEMAND – 3.5 MILLION METRIC TONS OF ORE/YEAR – WITH MIX OF RAW WATER AND PROCESS WATER

Total Water Demand (Raw + Process)   425.1 m³/h   Mean
                                      566 m³/h   Maximum

Plant Productivity: 91% of time

Figure 10. The mixture of tailings and water would be thickened to a 53% solids content before export to the tailings deposit. However, the addition of 181 cubic meters of water from the catchment for every 389.1 cubic meters of water from the ore processing plant would give the mixture of tailings and water an effective solids content of 43%, which is within the range for conventional tailings management with no thickening. The addition of catchment water to the tailings deposit is the opposite of the current practice of constructing diversion canals around the tailings deposit in order to prevent the entry of catchment water so as to reduce the water stored behind the tailings dam. Because of the use of cyanide in the ore processing plant, the recirculation of water from the tailings deposit has the potential to increase the concentrations of antimony, arsenic and mercury in the water with each passage through the ore processing plant. Portion of figure from VOGBR (2016b) overlain with English labels.

22

Adequacy of Reduction of Water Content of Stored Tailings

Although the predicted water consumption of the Volta Grande Project seems perfectly reasonable, it is important to consider how the water economy is achieved. The tailings deposit will receive both water (the spent cyanide leach) from the ore processing plant and the surface runoff from the watershed (see Figs. 3 and 10). Out of the free water that accumulates in the tailings deposit, 211.2 cubic meters of water per hour would be pumped back into the ore processing plant without water treatment and 197.8 cubic meters of water per hour would be pumped though a water filtration plant for removal of sediment before pumping to the ore processing plant (VOGBR, 2016b; see Fig. 10). The result of the use of the tailings deposit as, essentially, a water storage pond, is that there would always be free water on top of the tailings (see Fig. 11a) with 7 meters of free water by the end of the mining operation (see Fig. 11b). As a consequence, almost all of the tailings would be saturated with water (see Fig. 12a). Out of the 35.43 million cubic meters of tailings and water that would remain at the end of the mining operation, 32.36 million cubic meters would be saturated tailings, while 3.07 million cubic meters would be free water on top of the tailings (Brandt Meio Ambiente, 2016b).
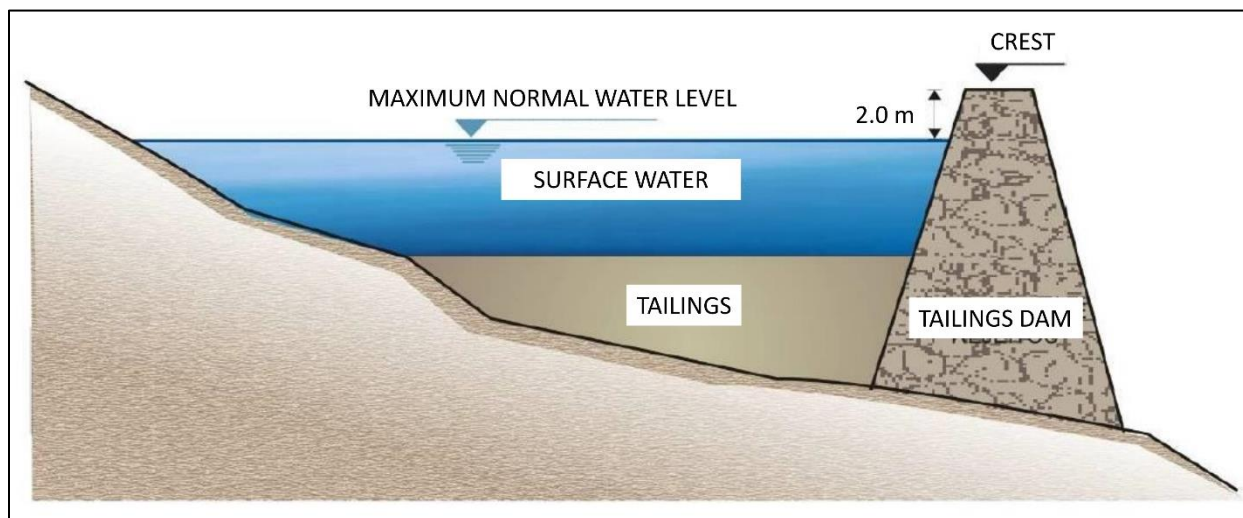

Figure 11a. The entry of catchment water into the tailings deposit and the lack of downstream discharge from the tailings dam would allow the tailings deposit to act as a reservoir of free water (water that is not stored in the pores between the tailings) for recycling into the ore processing plant (see Fig. 10). However, the result is that the tailings will be completely saturated with water. This is the opposite of the current practice of reducing the water content and lowering the water table within the tailings in order to reduce both the probability and the consequences of dam failure. Figure from VOGBR (2016b) overlain with English labels.

The use of the tailings deposit to capture surface runoff is a very unusual practice at the present time. In fact, it is far more common to construct a system of diversion channels to prevent the entry of catchment water into the tailings deposit in order to reduce the water content of the tailings (Vick, 1990). The mining company does plan to thicken the mixture of tailings and water to a 53% solids content before export to the tailings deposit. However, the addition of 181 cubic meters of water (surface runoff + precipitation – evaporation) for every 389.1 cubic meters of water from the ore processing plant (see Fig. 10) would give the mixture of tailings and water an effective solids content of 43%, which is within the range for conventional tailings management with no thickening.
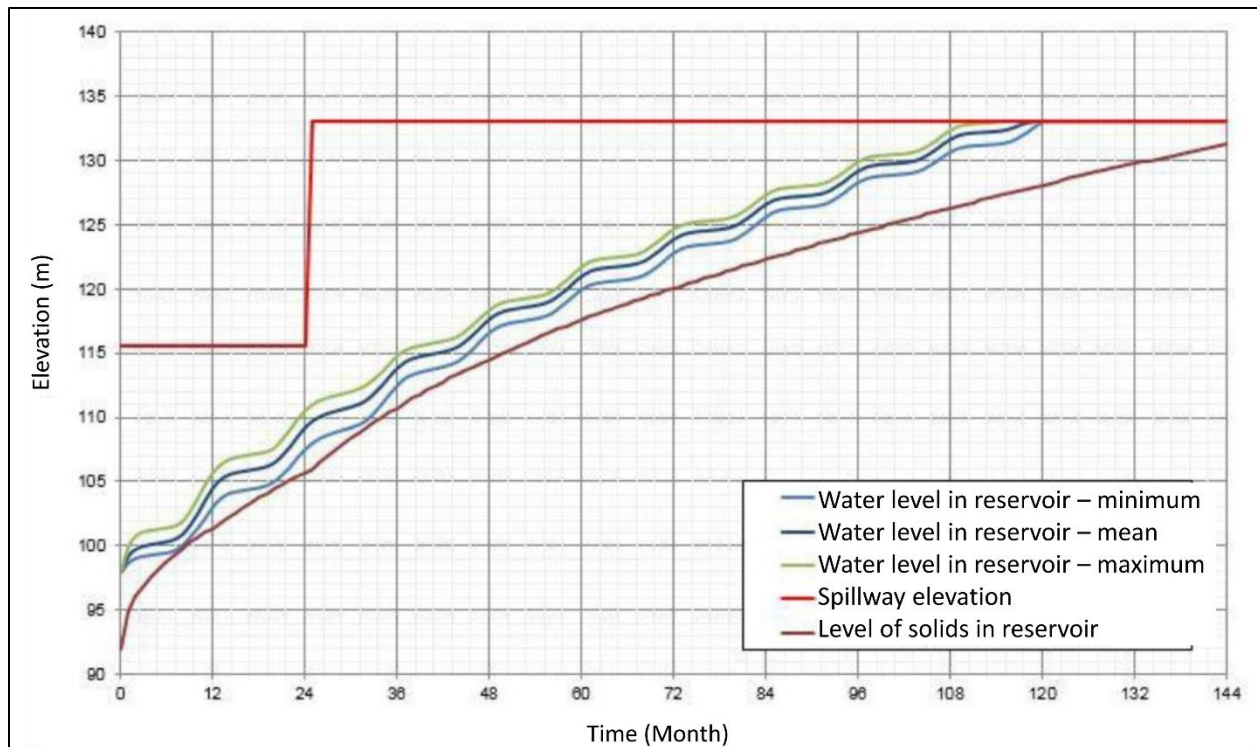
23

Figure 11b. The entry of catchment water into the tailings deposit and the lack of downstream discharge from the tailings dam would allow the tailings deposit to act as a reservoir of free water (water that is not stored in the pores between the tailings) for recycling into the ore processing plant (see Fig. 10). After 10 years of mining, the water level behind the tailings dam should be 7 meters above the level of the solid tailings (see Fig. 11a). The result is that the tailings will be completely saturated with water. This is opposite of the current practice of reducing the water content and lowering the water table within the tailings in order to reduce both the probability and the consequences of dam failure. Figure from VOGBR (2016b) overlain with English labels.

In contrast to the plan for the Volta Grande Project, the mining industry literature on the need to reduce both the probability and the consequences of tailings dam failure by lowering the water table and reducing the water content of the tailings is too vast to review here. Three recent examples should suffice. One of the "Key Messages" of Australian Government (2016) is that "Leading practice tailings storage methods seek to eliminate the potentially catastrophic risks associated with the release of tailings slurry from TSFs [Tailings Storage Facilities] by dewatering the tailings before deposition and by minimizing the containment of water in the TSF." Australian Government (2016) further clarifies, "An increasing number of mining operations employ dewatering to produce thickened and paste tailings and this is more likely to become more widespread in the future." In their review of the cause of failure of the tailings dam at the Mount Polley mine, Independent Expert Engineering Investigation and Review Panel (2015) wrote, "In accomplishing this objective [physical stability of the tailings deposit], BAT [Best Available Technologies] has three components that derive from first principles of soil mechanics: 1) Eliminate surface water from the impoundment 2) Promote unsaturated conditions in the tailings with drainage provisions 3) Achieve dilatant conditions throughout the tailings deposit by compaction." The authors continued, "Demonstrated technology for producing and placing filtered tailings (sometimes termed 'dry stack' tailings) is well-known in the industry…Its adoption and design practices are documented in the literature…Filtered tailings technology embodies all three BAT components…There are no overriding technical

24

impediments to more widespread adoption of filtered tailings technology." The first paragraph of "Study of Tailings Management Technologies" (sponsored by the Mining Association of Canada and the Mine Environment Neutral Drainage Program) stated, "Although one root cause has not been identified for all tailings dam failures, a common contributing factor to the higher consequence of failure includes the storage and behavior of water within the facilities. This has led the industry to reconsider alternatives to conventional tailings facilities, including dewatering tailings prior to deposition…" (Klohn Crippen Berger, 2017).

Figure IV-1 – Stability Analysis – Starter Dike: El. 121 m – Water Level for Normal Condition
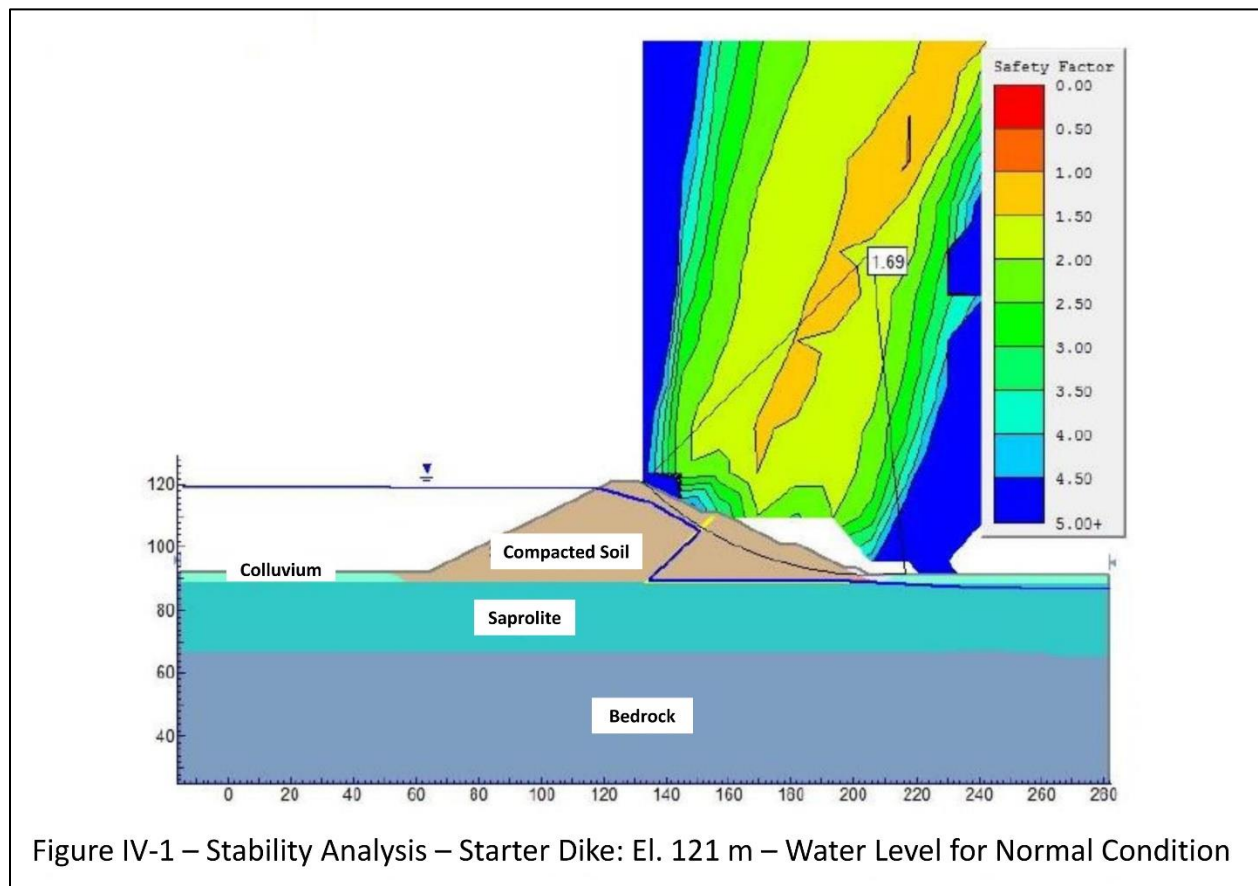
Figure 12a. The starter dike would have a factor of safety of 1.69, where the factor of safety is the minimum ratio of the shear resistance to the shear stress, considered over all possible failure surfaces. The calculated factor of safety exceeds the minimum value of 1.50 that is required by Brazilian tailings dam regulations (ABNT, 2017). However, the factor of safety was calculated only for the static condition and not for the dam response to seismic acceleration, contrary to the same tailings dam regulations that require design to withstand the Maximum Credible Earthquake (ABNT, 2017). No stability analyses have been provided for the final dike (see Fig. 8). Note the role of the internal drainage system (see Fig. 8) in lowering the water table within the starter dike. Figure from VOGBR (2016a) overlain with English labels.

Adequacy of Seismic Analysis and Design

Based upon the geometry of the tailings deposit, an assumed water table height, and the geotechnical parameters of the compacted soil and the foundation, the starter dike would have a factor of safety of 1.69 against failure by slumping or sliding (see Fig. 12a), which is reasonably greater than the minimum value (1.50) required by Brazilian tailings dam regulations (ABNT, 2017). The internal drainage system (yellow lines in Figs. 8 and 12a) would clearly play a critical

role in lowering the water table within the tailings dam (although not in the tailings stored behind the dam). Any failure of the internal drainage system that would allow the water table to rise about one-half the dam height on the downslope side of the starter dike would cause the factor of safety to drop below the minimum acceptable value (see Fig. 12b). I have not seen any document that carries out the same stability analysis for the final dike.
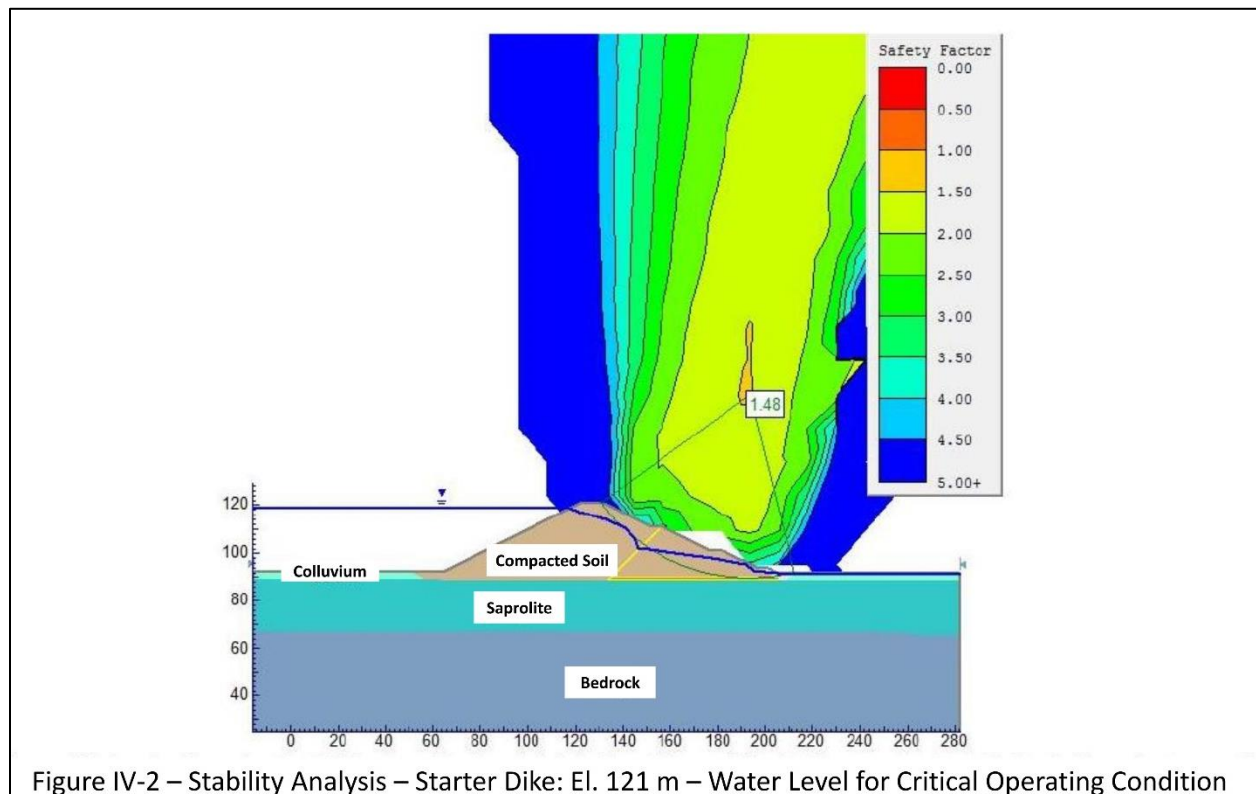

Figure IV-2 – Stability Analysis – Starter Dike: El. 121 m – Water Level for Critical Operating Condition

Figure 12b. The figure shows the critical level of the water table within the tailings dam at which the factor of safety would fall below the minimum value (1.50) required by Brazilian tailings dam regulations (ABNT, 2017). The factor of safety is the minimum ratio of the shear resistance to the shear stress, considered over all possible failure surfaces. However, the factor of safety was calculated only for the static condition and not for the dam response to seismic acceleration, contrary to the same tailings dam regulations that require design to withstand the Maximum Credible Earthquake (ABNT, 2017). No stability analyses have been provided for the final dike (see Fig. 8). Note the role of the internal drainage system (see Figs. 8 and 12a) in lowering or in failing to lower the water table within the starter dike. Figure from VOGBR (2016a) overlain with English labels.

It is most disturbing that the existing stability analyses were carried out only under static conditions and not under the condition of a design seismic acceleration. In fact, none of the documents of the 2016 EIS discuss a design earthquake or include any analysis of local or regional seismicity. This is surprising because the documents show maps of faults and fractures in the vicinity of the mining project site, including three possible faults intersecting at the exact site of the proposed tailings dam (see Figs. 13a-b; VOGBR, 2016a). However, these faults were discussed only in terms of their ability to transmit seepage of water from the tailings deposit, and not in terms of their ability to act as sources of seismicity.

As mentioned earlier, this failure to carry out seismic studies and to design a tailings dam to accommodate the Maximum Credible Earthquake (MCE) is in violation of current Brazilian tailings dam regulations (ABNT, 2017). It is disturbing that, in a presentation to FUNAI

(National Indian Foundation) in October 2019, Belo Sun Mineração (2019) was still claiming that the tailings dam had been designed in accordance with ABNT NBR 13.028/2006, even though those earlier tailings dam regulations had already been out-of-date for two years. In fact, the tailings dam design could have been consistent with the older tailings dam regulations, which did not require seismic studies or design for a particular earthquake (Franca, 2018). (See Franca (2018) for a comparison of the 2006 and 2017 tailings dam regulations. The author, Paulo Franca, has been connected with the Volta Grande Project, as he was the fourth author on the 2015 Feasibility Study (Chubb et al., 2015)).
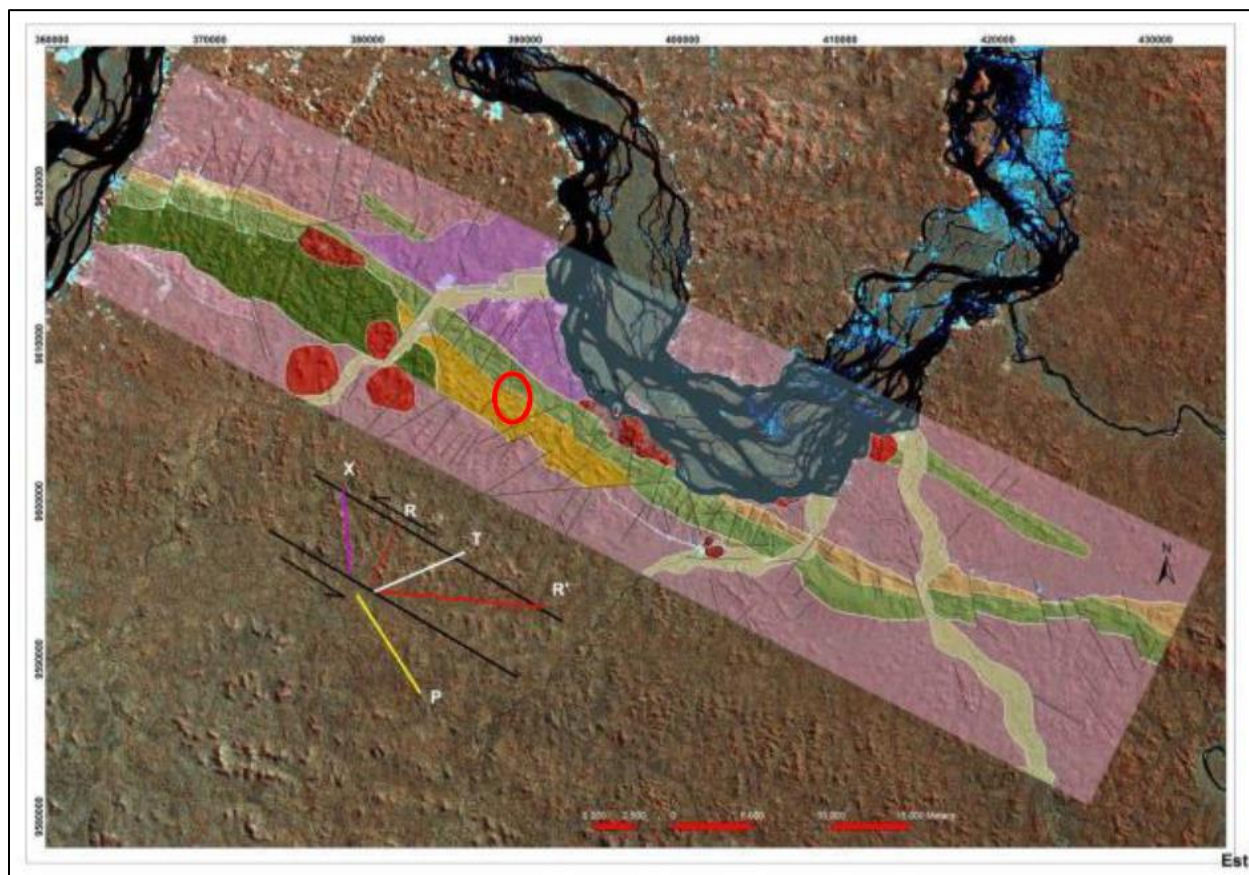

Figure 13a. A geological map superimposed onto a Landsat image shows possible faults with directions T, R, X, P and R' in the vicinity of the tailings deposit (red ellipse). (Compare with Fig. 2 for location). Although the figure was provided by VOGBR (2016a), there was no discussion of the ability of the faults to act as sources of seismicity that could impact the tailings dam. Figure from VOGBR (2016a).

Adequacy of Environmental Protection from Effects of Cyanide

It has already been mentioned that the use of cyanide to extract gold from crushed ore also has the potential to dissolve arsenic, antimony, and mercury. Moreover, the processes that are used to remove the gold from the cyanide solution and to destroy the cyanide will not remove the toxic by-products antimony, arsenic and mercury from the spent cyanide leach. Since, according to the plan for the Volta Grande Project, the cyanide leach would be endlessly recycled between the ore processing plant and the tailings deposit with no intervening water treatment (see Fig. 10), the cyanide leach has the potential to become increasingly enriched in

antimony, arsenic and mercury with each passage through the ore processing plant. The result could be the spill of a mixture of tailings and water that would be highly toxic to aquatic organisms in the Xingu River if the tailings dam ever failed.
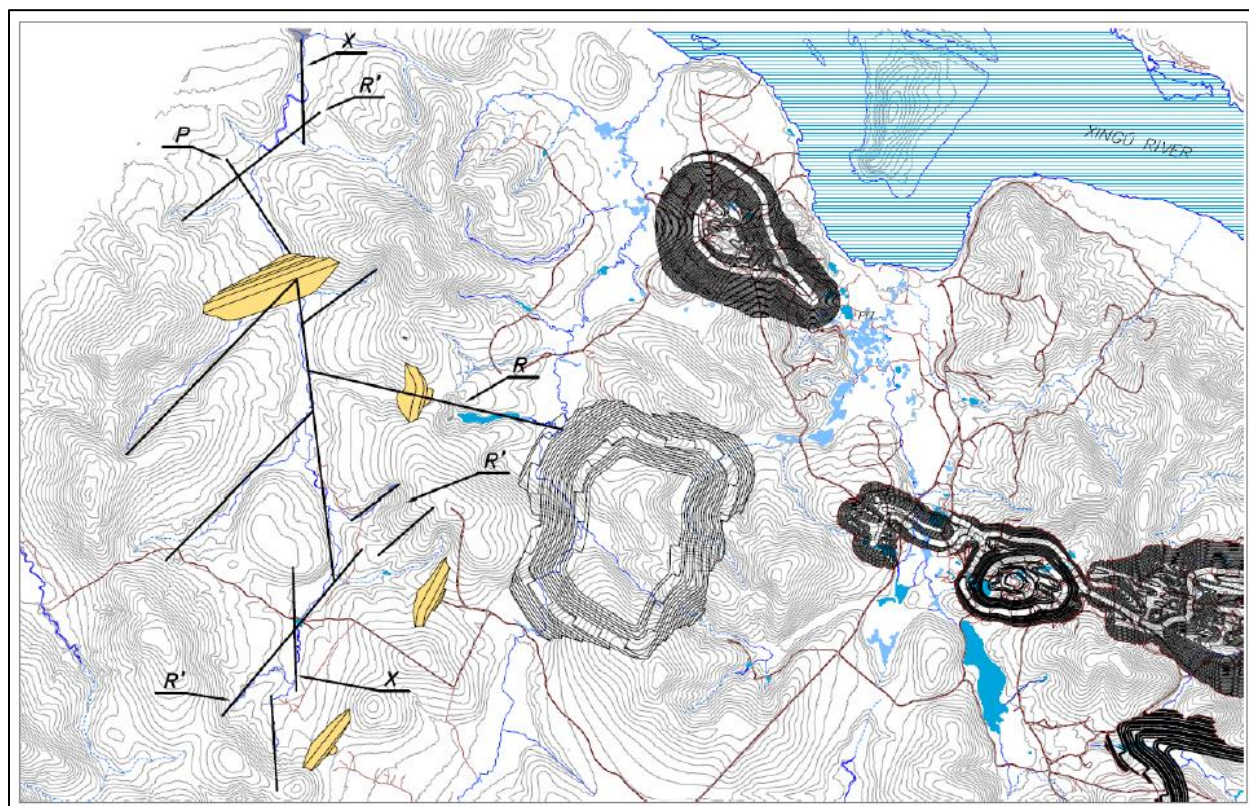

Figure 13b. VOGBR (2016a) provided a figure that showed possible faults in the vicinity of the tailings dam, but did not discuss the ability of the faults to act as sources of seismicity that could impact the tailings dam. The large yellow polygon is the principal tailings dam, while the three smaller yellow polygons are dikes around the perimeter of the tailings deposit. (Compare with Fig. 3 for location). Figure from VOGBR (2016a).

The point here is not to claim that the water in the tailings deposit would be highly enriched in toxic elements, but to point out that the possibility was never even investigated in the 2016 EIS. By contrast, the 2015 Feasibility Study (Chubb et al., 2015) repeatedly emphasized the high concentrations of arsenic in both the waste rock and the tailings. According to Chubb et al. (2015), "Of the 16 samples [of waste rock] classified as not dangerous and non-inert, arsenic was the parameter that exceeded guidelines most frequently (n = 12), with an average exceedance 30 times the Resíduo Solubilização [Solubilized Waste] guideline (0.01 mg/L)…The solubilized waste and free draining leach column studies completed by Belo Sun suggest that arsenic could be a parameter of concern in the contact water leaching through the WMF [Waste Management Facility]…Free draining leach columns and Resíduo Solubilização results indicated a potential for arsenic as a parameter of concern; the risk of untreated discharge from the seepage ponds needs to be further assessed…Six tailings samples were analyzed by the Resíduo Lixiviação (leachate waste) and Resíduo Solubilização (solubilized waste) methods; all six were not dangerous and non-inert, arsenic was the parameter that exceeded guidelines most frequently (n = 5), with an average exceedance 40 times the Resíduo Solubilização guideline (0.01 mg/L)…" The available documents from the 2016 EIS do not give any indication that the above

issue was considered any further or that any predictions were carried out concerning the final water quality of the tailings deposit.

Adequacy of Analysis of Consequences of Dam Failure

Based on a dam height $H = 44$ meters and a volume of stored tailings and water $V_T = 35.43$ million cubic meters, Eqs. (1)-(3) predict a spill volume $V_F = 9.84$ million cubic meters (27.8% of the stored tailings and water) and an initial runout of 41.4 kilometers along the Xingu River (see Fig. 2). The above is the most-likely scenario following dam failure and it would certainly impact the indigenous land of the Arara de Volta Grande do Xingu (see Fig. 2). The worst-case scenario would the spill of 100% of the stored tailings and water, which would result in an initial runout of 98.1 kilometers along the Xingu River according to Eqs. (3)-(4). Subsequent to the initial event, normal fluvial processes would continue to transport the spilled tailings farther down the Xingu River into the Amazon River and eventually into the Atlantic Ocean (see Fig. 1).

The time scale of the above events is also a matter of concern. Although the edge of the tailings deposit is 1535 meters from the banks of the Xingu River, the tailings flood would more likely flow along an existing stream channel for 2228 meters before reaching the Xingu River (see Fig. 3). There have not been many measurements of the velocities of tailings flow slides, but they have ranged from 20-160 kilometers per hour (Jeyapalan, 1981). According to Petley (2019), the tailings flow slide following the 2019 failure of the tailings dam in Brumadinho, Minas Gerais (see Table 1) accelerated to 120 kilometers per hour and then slowed to 66 kilometers per hour. The lower limit of 20 kilometers per hour apparently accounts for the new mining legislation in Minas Gerais that prohibits the construction or expansion of a tailings dam where there is a population residing either 10 kilometers downstream of the dam along the course of the valley or within the zone that could be reached by the tailings flood within 30 minutes, whichever is farther (Assembleia Legislativa de Minas Gerais, 2019). Using the most conservative value of 20 kilometers per hour, the tailings flood from a failure of the tailings dam would arrive on the banks of the Xingu River in under 7 minutes, and would cover the initial runout (41.4 kilometers), reaching and passing the indigenous land of the Arara de Volta Grande do Xingu, in about two hours (see Fig. 2).

It is difficult to reconcile the above results with the conclusions reached by Brandt Meio Ambiente (2016a). According to the 2016 EIS, the tailings flood would reach the banks of the Xingu River in 97 minutes, corresponding to a tailings flow velocity of 1.4 kilometers per hour. The above velocity is quite slow. The vast majority of streams at flood stage have velocities in the range 4-11 kilometers per hour (Leopold, 1994). No available document has explained the details of the calculation. However, a hint is given in Brandt Meio Ambiente (2016a), which lists as one of the assumptions of the calculation "*Critério de parada: atingir o Rio Xingu* [Stopping criterion: Reaching the Xingu River] (see Fig. 14). There is no physical basis for the assumption that the tailings would come to a stop upon reaching the Xingu River, especially not a river with a minimum discharge of 700 cubic meters per second (Higgins, 2020).

Adequacy of Plan for Safe Closure of Tailings Dam

Brandt Meio Ambiente (2016b) acknowledges that after the end of the mining operation, the tailings dam and tailings deposit would remain a "*destaque permanente na paisagem*"

[permanent highlight of the landscape]. This means that it will be necessary to ensure that the tailings dam will be stable and will be able to confine the tailings in perpetuity. The only concrete plan for achieving permanent stability is to drain the free water into the Oeste water storage pond (see Fig. 3). In turn, there is an unsubstantiated promise that the water in the storage ponds will meet Brazilian environmental standards, so that the storage ponds will be drained, unless there is community interest in using the ponds for other purposes.
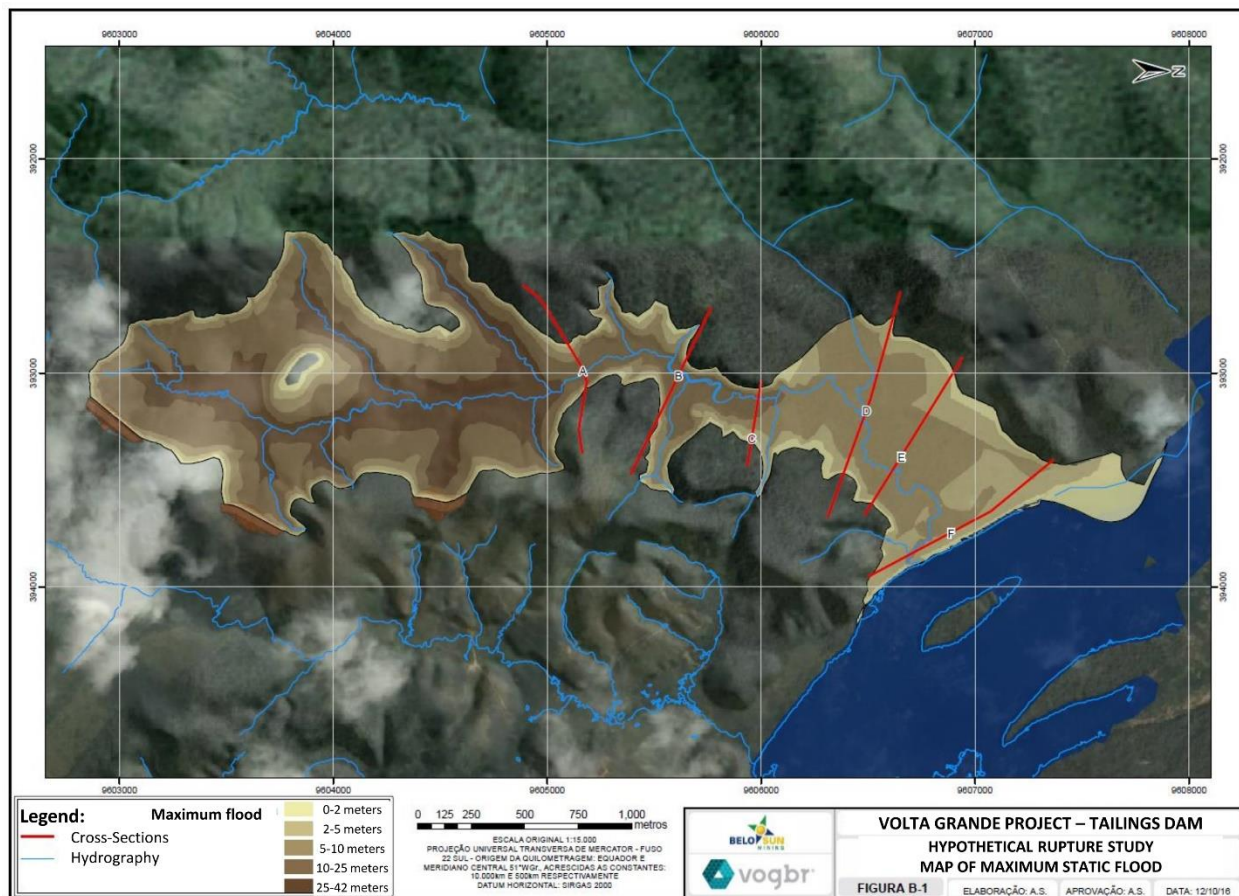

Figure 14. The dam break analysis was flawed in that it assumed that the tailings flood would cease when the tailings reached the Xingu River (Brandt Meio Ambiente, 2016). Cross-section A is the edge of the tailings dam (compare with Fig. 3 for location, but note difference in north arrows). The figure is overlain with English labels and comes from a report that was not available to the author.

Otherwise, the 2016 EIS contains only a promise to figure out later how to permanently stabilize the tailings dam. In particular, the plan for safe and permanent closure of the tailings dam does not become any more detailed than the following: *"O fechamento do empreendimento pressupõe vistorias finais de Engenharia para averiguar a qualidade dos trabalhos de controle físico das superfícies da área diretamente afetada no Projeto Volta Grande. Todas as estruturas, durante a fase de fechamento serão objeto de avaliação para assegurar a estabilidade física do terreno e das estruturas remanescentes. A Engenharia da empresa, ainda durante a operação, mas também durante a fase de fechamento, irá realizar as obras necessárias para garantir esta estabilidade. Todas as estruturas, antes da saída da empresa, serão objeto de avaliação criteriosa quanto a sua estabilidade de longo prazo… Á medida que o Plano de Fechamento for sendo atualizado, chegando finalmente a um Plano Executivo de Fechamento, estes projetos de*

adequação das barragens para o período após a saída da empresa mineradora precisam ser detalhados especificamente... Esta versão do Plano de Fechamento é a inicial, podendo, portanto, esta forma de tratamento do sistema da barragem de rejeito, do Projeto Volta Grande, estar sujeita a modificações, com base em novas tecnologias ou métodos de fechamento, ou mesmo propostas alternativas de uso futuro diferenciadas das atualmente imaginadas" [The closure of the project requires final engineering inspections to ascertain the quality of the physical control works on the surfaces of the area directly affected by the Volta Grande Project. All structures, during the closing phase, will be subject to evaluation to ensure the physical stability of the land and of the remaining structures. The company's Engineering, even during the operation, but also during the closing phase, will carry out the necessary works to guarantee this stability. All structures, before the departure of the company, will be subject to a careful assessment as to their long-term stability…As the Closure Plan is being updated, finally reaching an Executive Closure Plan, these projects for the adequacy of the dams for the period after the departure of the mining company will be specifically detailed…This version of the Closure Plan is the initial one, therefore, this form of treatment of the tailings dam system, of the Volta Grande Project, may be subject to changes, based on new technologies or methods of closure, or even alternative proposals for future use different from those currently imagined] (Brandt Meio Ambiente, 2016b). There is certainly no plan to continue in perpetuity the monitoring, inspection and maintenance of a tailings dam that will be expected to confine tailings in perpetuity.

DISCUSSION

Annual Probability of Failure of Tailings Dam

At this point, the annual probability of failure of the tailings dam for the proposed Volta Grande Project can be considered. An annual probability of failure is estimated by beginning with a base failure rate for all tailings dams (or all tailings dams in a particular category), after which the factors that could increase or decrease the probability of failure for a particular tailings dam are considered. It has already been mentioned that the Brazilian tailings dam failure rate has been 0.06% per year (see Table 1 and Fig. 4), although that must be an underestimate because it assumes that all current tailings dams have been in existence since 1986. Since the global failure rate has been 0.06-0.14% per year (Davies, 2002) and the failure rate in British Columbia has been 0.17% per year, a base annual failure rate of 0.1% is probably reasonable for tailings dams in Brazil.

For the tailings dam for the proposed Volta Grande Project, the only factor that would lower the probability of failure below the baseline is the method of downstream construction, which is the safest of the common construction methods. On the other hand, the following factors would tend to increase the probability of failure in order of importance (1 = most important):

1) The tailings would store an excessive amount of water. In particular, all tailings would be saturated and there would be 7 meters of free water on top of the tailings.
2) No studies of local or regional seismicity have been carried out.
3) There has been no analysis of the stability of the tailings dam in response to seismic acceleration.
4) Intersecting geological faults have been mapped at the site of the proposed tailings dam.

The second and third factors listed above require careful consideration. It is possible that the Volta Grande Project would be located in a region of insignificant seismicity. It is also possible that the tailings dam would be stable in response to the Maximum Credible Earthquake (MCE), even though that response has never been calculated, nor has the acceleration due to the MCE been determined. However, an annual probability of failure is essentially a subjective measure of the lack of confidence in the survivability of a structure (Vick, 2002). Thus, any lack of knowledge (such as the lack of any seismic studies) must decrease the confidence in survivability and thus, increases the assessment of the probability of failure.

Although, based on engineering principles, downstream tailings dams ought to be safer than upstream or centerline dams, it is difficult to quantify how much safer, simply based upon the statistics of past dam failures. Out of the 356 tailings dam failures listed in the database of World Mine Tailings Failures (2019), the construction method is unknown for 171 failures (48%). It is more important that there is no global database of the numbers of tailings dams that have been constructed by each method. Failures of downstream dams certainly have occurred. The same database (World Mine Tailings Failures, 2019) lists 26 failures of downstream dams, or 14% of all failures for which the construction method is known. Those failures of downstream dams include the failure of a tailings dam at the Ajka Alumina Plant in Hungary in 2010, which released 1 million cubic meters of tailings, resulting in 10 deaths. There are two additional known cases of dam failures for which the dam started as an upstream dam, although later raises used the upstream method (World Mine Tailings Failures, 2019). These two cases are the failure of a dam owned by AngloGold Ashanti in Crixás, Goiá, in 1994 (see Table 1), and the dam that failed near Baia Mare, Romania, in 2000, releasing 100,000 cubic meters of cyanide-contaminated water.

One approach is to consider the numbers of tailings dams constructed by each method in Brazil, which has been fairly well-documented (Agência Nacional de Mineração, 2019a), and assume that those same percentages roughly apply to the rest of the world. Out of 769 tailings dams in Brazil, 152 have been constructed using the downstream method, while 81 dams have an unknown construction method, so that downstream dams comprise 22% of the dams with a known construction method. Compared with the 14% of all global failures for which the construction method is known, it would appear that downstream dams might be twice as safe as other dams, but certainly not an order of magnitude (ten times) safer. On that basis, it could be assumed that the downstream construction method lowers the annual probability to 0.05%, but no lower.

It is not possible to objectively quantify, based on the past history of tailings dam failures, the increased probability of failure due to the four detrimental factors of excessive water, no seismic studies, no seismic stability analysis, and the presence of intersecting geological faults at the proposed tailings dam site. Simply put, there is no database of tailings dams for which no seismic studies were carried out. On the other hand, from a subjective standpoint, the four detrimental factors are so detrimental that they must increase the annual probability of failure by at least an order of magnitude. Thus, combining the positive factor of downstream construction and the four detrimental factors leads to an annual probability of failure of at least 0.5%.

A probability of tailings dam failure of 0.5% per year would not be acceptable under any circumstances. This probability would be equivalent to a tailings dam failure in Brazil every three months (based on 769 tailings dams in Brazil). This probability is far greater than the FEMA (2005) requirement of design of dams with even Low Hazard Potential to be able to

withstand an earthquake with a 10,000-year return period (corresponding to annual probability of exceedance of 0.01%). An annual probability of failure of 0.5% would be equivalent to a probability of failure of 5.8% during at least one year of the 12 years of the mining operation. Of course, the possibility of tailings dam failure does not end when the mining operation ends. The possibility of dam failure ends only when the dam has been placed into a state of permanent stability with no need for any further monitoring, inspection or maintenance. As already discussed, at present, there is no plan for achieving such a permanent state.

Technical Challenges of Filtered Tailings

The parent company, Belo Sun Mining, has apparently already decided that the current plan for the Volta Grande Project is unworkable. In numerous corporate communications in 2019, the company stated that they were abandoning the current plan in favor of a filtered tailings storage facility. On January 30, 2019, the President and CEO of Belo Sun Mining wrote to MiningWatch Canada, "As you may know the Government of Brazil, Minister of Environment, Mr. Ricardo Salles stated (29 Jan 2019) that mining companies must look for alternatives to wet tailings. Belo Sun has been undertaking the test work and engineering on a filtered tailing (dry stack) prior to the Brumadinho accident, and will be complying with this mandate and plan to modify our tailing deposal to a filtered (dry stack) system that will not require a retaining dam…We feel that the mining industry needs to move away from wet tailings and Belo Sun will be moving to present to the government ministries a filtered and stacked system for the Volta Grande Project" (Belo Sun Mining, 2019a). In information provided to investors in May 2019, Belo Sun Mining (2019b) wrote that, during the first three months of 2019, "the Company engaged SRK to undertake a scoping study to review dry stack [filtered] tailings storage." Finally, a slide in a July 2019 presentation to investors states under the heading "Engineering Optimization" the bullet point "Dry stack filtered tailings" (Belo Sun Mining, 2019c).

It should be noted that the President and CEO of Belo Sun Mining is incorrect in stating that filtered tailings do not require a dam. Most typically, filtered tailings facilities are constructed with an outer shell of compacted tailings (sometimes called the "structural zone") surrounding an inner core of uncompacted or lightly compacted tailings. The structural zone fulfills the exact same function as a dam, that is, it is an engineering structure that prevents the flow of water or other materials. Klohn Crippen Berger (2017) has emphasized that "if filtered tailings are placed in a stand-alone facility (pile/stack), the outer slopes must maintain structural stability (similar to a dam or a waste dump), particularly under seismic loading conditions."

The inner core of a filtered tailings facility is, in fact, a requirement for the storage of tailings that left the filtering plant with too much water for proper compaction. Crystal et al. (2017) have emphasized that target water contents for filtered tailings are rarely achieved. According to Crystal et al. (2017), "Commonly, projects are specifying (or promising) a target filter-cake moisture at the limit of the filter performance (including at the limit of the thickener's ability to deliver feed at the required solids ratio). This has caused numerous examples where the operating performance does not consistently meet the target…Essentially, irrespective of site, ore body type, or filter press manufacturer, a 15% moisture content remains a typical target, while tracking of day-in and day-out moisture contents of filter cakes demonstrates that achievable moisture contents are often in the range of 17 to 18% when things are running smoothly and can be up to 20 to 23% when off-spec…'Targets' may be cited or promised, but achievable filter

cake moisture contents and the variability of the process are not generally within the tailings engineer's control." The solution is to set aside an inner core (a region away from the outer slopes) for placement of tailings that cannot be compacted and to confine the inner core with a structural zone (a dam). Crystal et al. (2017) continue, "The tailings engineer can, however, specify acceptable moisture contents for different areas of the dry stack, depending on stacking strategies. For example, external structural zones may have more stringent criteria than non-structural zones, for which reduced constraints may be allowed." The three authors of Crystal et al. (2017) are all employees of SRK Consulting, which has been hired by Belo Sun Mining to design the filtered tailings storage facility (Belo Sun Mining, 2019b) and the paper is available on the SRK Exploration Services website.

Although the transition to a filtered tailings storage facility is, without question, a step in a positive direction, such a plan would still need to overcome numerous technical challenges. The following are a few of the challenges that would still need to be addressed:

1) Given the current difficulty in achieving optimum water contents for proper compaction, the difficulty becomes even more acute in areas of high rainfall. Even if the tailings leave the filter presses with the proper water content, they can still be rewetted by precipitation and, thus, become too wet for even partial compaction. Therefore, it will be necessary to have sufficient temporary storage space for filtered tailings that will need to dry before compaction.

2) In an area with high rainfall, it will be crucial to prevent the rewetting of the tailings after storage in the filtered tailings facility. At a minimum, this will require appropriate diversion channels to prevent the entry of surface runoff onto the filtered tailings.

3) If the tailings deposit is no longer used as a means of capturing surface runoff, another source of water for the mining operation must be found.

4) It will still be necessary to carry out local and regional seismic studies and to design the filtered tailings storage facility so that it can withstand the Maximum Credible Earthquake.

The disturbing aspect of this stated transition to filtered tailings is that Belo Sun Mineração has provided the opposite information to the Brazilian organizations and regulatory authorities. In their presentation to FUNAI in October 2019, Belo Sun Mineração (2019) described the same plan for storage of wet tailings that was described in the 2016 EIS. It is most disturbing that the two Indigenous Component Studies (JGP Consultoria e Participações, 2020a-b) also describe the same plan for storage of wet tailings that was described in the 2016 EIS. This provision of contradictory sets of information to different audiences on the part of Belo Sun Mining and its Brazilian subsidiary is not reassuring.

CONCLUSIONS

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

1) The use of the tailings reservoir for capture of surface runoff is contrary to the mining industry trend of reducing the water stored in tailings reservoirs in order to reduce both the probability and consequences of dam failure.

2) The tailings dam has not been designed for any seismic safety criterion, in violation of Brazilian tailings dam regulations.

3) There has been no study of local or regional seismicity, although intersecting geological faults have been mapped at the site of the proposed tailings dam, which is also in violation of Brazilian tailings dam regulations.

4) The recycling of cyanide leachate could result in tailings water that is highly enriched in antimony, arsenic and mercury.
5) In the most-likely dam failure scenario (release of 28% of the stored tailings), the initial runout of tailings would cover 41 kilometers along the Xingu River with significant impact on the Arara de Volta Grande do Xingu indigenous land. Under the worst-case scenario (release of 100% of stored tailings), the initial runout would cover 98 kilometers along the Xingu River. Following the initial runout, normal fluvial processes would transport the tailings into the Amazon River and the Atlantic Ocean.
6) There is no plan for safe closure of the tailings dam, except for draining the free water into a water storage pond.
7) The annual probability of failure of the tailings dam would be at least 0.5%, which is unacceptably high.
8) Although the mining company has stated to investors that they will abandon the current plan for storage of wet tailings in favor of filtered tailings, there are still significant technical challenges to the storage of filtered tailings in areas with high rainfall.
9) It is disturbing that the mining company has been providing contradictory information regarding their tailings storage plan to investors and to the Brazilian regulatory authorities.

RECOMMENDATIONS

Based on the high probability of failure of the proposed tailings dam, the Volta Grande Gold Project should be rejected by the Brazilian regulatory authorities without further consideration. Simply the provision of conflicting information to investors and to Brazilian regulatory authorities should be sufficient cause for rejection.

ACKNOWLEDGEMENTS

I am grateful to Kirsten Francescone of MiningWatch Canada for providing me with an e-mail from the President and CEO of Belo Sun Mining.

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