RISK ANALYSIS OF THE TAILINGS DAMS AT THE RIOTINTO MINE, ANDALUSIA, SPAIN
Risk Analysis of the Tailings Dams at the Riotinto Mine, Andalusia, Spain
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Report prepared at the request of London Mining Network
Submitted on August 6, 2019

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Figure 1. The objective of this study is to evaluate the risk of failure of the tailings dams at the Riotinto Mine, which includes both the probability and the consequences of failure. Photo of Aguzadera Dam taken by the author on June 19, 2019.

LIGHTNING SUMMARY

The probability of failure due to liquefaction of the upstream tailings dams at the Riotinto Mine in Andalusia, Spain, is very high. The water table directly behind the Aguzadera Dam is only 2.9 meters below the surface and uncontrolled seepage occurs through the downstream embankment at the same elevation, indicating that both the dam and tailings are nearly completely saturated with water.
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The Riotinto Mine in Andalusia, Spain, exports a mixture of mine tailings and water (35% solids) to two reservoirs, Aguzadera and Cobre. A third reservoir, called Gossan, stores the water that is recycled from the tailings ponds. The tailings dams were constructed from the coarser fraction (sands) of the tailings using the upstream method, so that loose, uncompacted tailings underlie the dams. Most recently, the dams were raised by constructing embankments of mine waste rock on top of and downstream from the sand dams. Although the Aguzadera reservoir has received no tailings for 12 months, the water table directly behind the dam is only 2.9 meters below the surface, while uncontrolled seepage occurs through the downstream embankment at the same elevation, indicating that both the dam and tailings are still nearly completely saturated with water. The saturated state of the dam is further indicated by the precipitation of iron sulfate in the seepage from the dam. Although a wide beach of tailings sand is required to prevent dam failure due to flooding and liquefaction, the pronounced desiccation cracks behind the dam indicate a mixing of sands and slimes, so that the beaches are non-existent. The mixing of sands and slimes promotes liquefaction by preventing drainage of the sands and maintaining the sands in an unconsolidated state. Based on the above, the probability of dam failure due to liquefaction is very high. Furthermore, the appearance of mud in both the controlled seepage (drainage tubes) and the uncontrolled seepage suggests the beginning of dam failure by internal erosion. Although existing stability analyses indicate a high factor of safety, they are irrelevant because they assume a low water table. The dams were designed to withstand a 500-year flood, which is not consistent with international standards and proposed changes to Spanish legislation that would require designs to withstand the 10,000-year flood or the Probable Maximum Flood. The existing analysis of the consequences of failure is inadequate in that it neglects the possibility of a chain breakage of all three dams, neglects the impacts on mineworkers and on the village of Sotiel Coronada (40 km downstream), assumes a spillage of only 35% of the contents behind a single dam, and uses an empirical formula for the time of breach formation that does not use data from tailings dams and which would be irrelevant for failure due to liquefaction. The failure to thicken the tailings before storage has been justified by misinterpreted laboratory sedimentation tests and is inconsistent with current industry practice.
OVERVIEW

The Riotinto Mine is an open-pit copper mine operated by Atalaya Mining in the province of Huelva, Autonomous Community of Andalusia, southern Spain (see Figs 1-2). The mine currently processes 9.5 million metric tons of ore per year with plans to expand to 15 million metric tons per year (Atalaya Mining, 2019a). Given that the grade of the ore is 0.41% copper and that the mine produces a copper concentrate with 22% copper (Ore Reserves Engineering, 2018), each year of current production results in over 9.3 million metric tons of waste. These waste materials that remain after processing of the ore are called mine tailings and are stored in the Cobre and Aguzadera tailings reservoirs (also called tailings ponds or tailings storage facilities or tailings management facilities; see Fig. 3). Another type of waste (called mine waste rock) is the rock that must be removed to arrive at the ore body. The storage of mine waste rock will not be discussed in this report. The Cobre and Aguzadera reservoirs are each confined by a tailings dam, although the two reservoirs also share a common dam wall (see Figs. 1 and 3). Excess water from the tailings reservoirs is pumped behind a third dam into the Gossan reservoir. Since the Cobre reservoir is upstream from the Aguzadera reservoir and the Gossan reservoir is upstream from both tailings reservoirs, the three dams could fail in a chain reaction (see Fig. 3).
Figure 2. Atalaya Mining operates the Riotinto copper mine in the province of Huelva, Autonomous Community of Andalusia, southern Spain. Figure from Ore Reserves Engineering (2018).
Figure 3. Tailings from the Riotinto Mine are stored behind tailings dams in the Cobre and Aguzadera tailings reservoirs. The Aguzadera and Cobre reservoirs share a common dam wall. Excess water from the tailings reservoirs is pumped behind a dam in the Gossan reservoir. A perimetral canal isolates the Aguzadera reservoir from the rest of the watershed. Since the Cobre reservoir is upstream from the Aguzadera reservoir and the Gossan reservoir is upstream from both tailings reservoirs, the three dams could fail in a chain reaction. Background is Google Earth image from July 16, 2013.

The objective of this report is to answer the following question: What is the risk of failure of the tailings dams at the Riotinto Mine? The objective can be subdivided into the following questions:

1) What is the probability of failure of the tailings dams?
2) What would be the consequences of failure of the tailings dams?

Before discussing the methodology for addressing the questions, the subject of tailings dams will first be reviewed with emphasis on the aspects that are most relevant to the tailings dams at the Riotinto Mine. A much more complete treatment of this subject can be found in the standard textbook on tailings dams by Vick (1990) and in dam safety guidelines from governmental agencies and professional organizations. The review of tailings dams will be followed by summaries of the most recent description of the tailings dams at the Riotinto Mine (Golder Associates, 2016), the most recent evaluation of the safety of the tailings dams (Ramírez and Lain, 2016), and the most recent evaluation of the consequences of dam failure (Ayesa, 2014).
REVIEW OF TAILINGS DAMS

Methods of Tailings Dam Construction

All methods of tailings dam construction are means of taking advantage of the very different physical properties of the two sizes of tailings, which are sands (larger than 0.075 mm) and slimes (smaller than 0.075 mm). These two sizes are separated by gravity in the tailings deposit. Normally, a mixture of tailings and water is discharged into the tailings deposit from the crest of the dam through spigots that connect to a tube that comes from the ore processing plant (see Fig. 4). 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 from suspension. It should be noted that the beach is essential to prevent the pond from reaching the crest of the dam.

Figure 4. 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. The narrow beach (especially on the opposite side, where the beach is almost nonexistent) makes the dam susceptible to flood failure. The absence of desiccation cracks indicates the high sand content on the beach (compare with Figs. 23a-d). Photo taken by the author on September 27, 2018.
Each of the three common methods of tailings dam construction (upstream, downstream and centerline) begins with an starter dike, which is constructed from natural soil, natural rock fill, mine waste rock, or tailings from a previous episode of ore processing (see Figs 5a-c). In the upstream construction method, successive dikes are built in the upstream direction as the level of stored tailings increases. It is most common to build successive dams from mine waste rock 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 (see Fig. 5a).

Figure 5a. 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 Chile and Brazil and would be illegal according to the new proposed legislation in Ecuador. 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 (2018).
The downstream construction method is the most expensive because it requires the largest amount of construction material (compare Figs 5a and 5b). In this method, successive dikes are constructed in the downstream direction as the level of stored tailings increases. In fact, this method of construction is not very different from the construction of an earthen dam for water retention. The differences are that a water retention dam would be completely constructed from a suitable natural soil or rock fill (instead of tailings or mine waste rock) and would be completely constructed before filling the reservoir with water. In addition, a water retention dam must be inspected and maintained or it must be dismantled. It is not possible to simply abandon a dam or it will eventually fail. However, a tailings dam must somehow be maintained forever, unless the tailings can be moved to another location or permanently encapsulated.

**Figure 5b.** 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 5a and 5b). Figure from TailPro Consulting (2018).
The centerline construction method is a balance between the advantages and disadvantages of the downstream and upstream construction methods (compare Figs 5a-c). In this method, successive dikes are built 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 (see Fig. 5c). Although there are little data on the frequency of different types of tailings dam construction, the centerline construction method is probably the most common method in the world for building tailings dams. The means of avoiding catastrophic failures of tailings dams, with particular emphasis on upstream tailings dams, will be discussed after reviewing the common causes of tailings dam failures.

Figure 5c. 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. 5a-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. Therefore, the dams constructed by this method are suitable for the temporary, but not permanent, storage of water. Currently, the centerline construction method is the most common method in the world for building tailings dams. Figure from TailPro Consulting (2018).
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. In the case of the tailings dam at the Highland Valley Copper Mine (see Fig. 4), 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.

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 lengthening the hydraulic flow paths (for example, by decreasing the slopes of embankments) and by forcing water to exit at the base of dams rather than along the face (for example, by installing appropriate drains). The installation of filters is usually regarded as essential in order to trap any solid particles that would be dislodged by the flow of water through the dam. Since the tailings dams at the Riotinto Mine were constructed on slate, foundation failure is not an issue and will not be discussed further.

Figure 6. 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 promoted 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. 4). Figure from DoITPoMS (2019).
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. 6, 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. 6, 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.

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. 4). It should be clear that the key to avoiding liquefaction is to keep the water table 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.

**Design and Operation of Upstream Tailings Dams**

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. 5a). Thus, even if the dam temporarily maintains its structural integrity while the underlying tailings liquefy, the dam could fail by either falling into or sliding over the liquefied tailings. Dams constructed using the centerline method retain some vulnerability to failure during liquefaction because there are still some uncompacted tailings underneath the dikes (see Fig. 5c). 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. 5b). As mentioned earlier, a downstream tailings dam is not much different from an earthen water retention dam. Of course, proper design and construction are still needed to prevent liquefaction of the dam itself even when the downstream method is used.

For the above reasons, the use of the upstream method for construction of tailings dams is illegal in Chile and Brazil (Ministerio de Minería, 2007; Agência Nacional de Mineração, 2019; Assembleia Legislativa de Minas Gerais, 2019). The new Brazilian legislation, which was a response to the failure of the Fundão Dam at the Samarco Mine in
2015 and Dam I at the Córrego do Feijão Mine in 2019, both of which were upstream dams, even requires the decommissioning of all existing upstream tailings dams by August 2021. The new legislation in Ecuador that has been proposed by the Ministerio de Energía y Recursos Naturales no Renovables [Ministry of Energy and Non Renewable Natural Resources] would not only prohibit the upstream method, but would severely restrict the use of the centerline method. According to the proposal, “El crecimiento de eje central sólo se autorizará bajo condiciones excepcionales, en donde la morfología o espacio del terreno no permitan el crecimiento hacia aguas abajo y solo será aplicable a zonas de baja sismicidad, para este método se debe reforzar la construcción y considerar mayores criterios de seguridad” [The centerline method will be authorized only under exceptional conditions, in which the land shape or space does not allow the downstream method and will be applicable only in areas of low seismicity; for this method the construction should be reinforced and should consider stricter safety criteria] (Ministerio de Energía y Recursos Naturales no Renovables, 2019).

In a classic paper, Martin et al. (2002) listed the ten rules for upstream tailings dams. According to the authors, “any omission creates immediate candidacy for an upstream tailings dam to join the list of facilities that have failed due to ignoring some or all of the rules.” The second rule is the need for a tailings beach that is sufficiently wide to prevent dam failure due to flooding or to collapse of the dam into the underlying tailings after liquefaction (Fig. 7 shows the tailings dam and the tailings beach as a single unit that must be wide enough to resist the impact of the underlying liquefaction). No recommendations for the minimum width of the tailings beach were given besides the above requirement (Martin et al., 2002). However, the new Ecuadorean proposal has recommended beach widths of 200 m or one-third the length of the tailings reservoir, whichever is smaller (Ministerio de Energía y Recursos Naturales no Renovables, 2019).

**Figure 7.** Tailings dams constructed using the upstream method should have beaches that are wide enough to prevent collapse of the dam after liquefaction of the uncompacted tailings underneath the dam. The diagram from Martin et al. (2002), which shows the beach and tailings dam as a single unit, illustrates a particular dam design that violates the “ten rules” of upstream dam design. The dam is too steep and should have an inclination of less than 1V:4H in order to prevent undrained shear failure. In addition, saturated tailings should not be present beneath the dam. (Appropriate drains should ensure that, beneath the dam, the water table should be nearly at the base of the tailings reservoir.) Figure from Martin et al. (2002).
Martin et al. (2002) presented Fig. 7 as an example of an upstream tailings dam design that violated six of the ten rules. The most important problem is that the design allows for saturated tailings underneath the dam. Ideally, underneath the dam, the water table should be nearly at the base of the tailings reservoir with all seepage exiting from the base of the starter dike. Second, the stability of the dam should have been evaluated under the assumption that the tailings and dam were saturated (a worst-case scenario), rather than assuming that the water table would remain at one-half of the height of the dam. Finally, the slope of the dam in Fig. 7 is too steep. According to Martin et al. (2002), “If an upstream constructed dam is raised at a slope steeper than 4H:1V [4 meters horizontal for 1 meter vertical], the likelihood of a static undrained failure [failure under saturated conditions] due to minimal trigger is increased.” European Commission (2009) recommended slopes no steeper than 3H:1V for dams of any construction type that store tailings from the mining of any base metals.

**Design Floods and 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 width of the tailings beach, the dimensions of the perimetral canal, or any other aspect of a tailings reservoir. 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 floods and earthquakes will be considered, which are the guidelines of the (U.S.) Federal Emergency Management Agency (FEMA, 2005, 2013), U.S. Army Corps of Engineers (USACE, 1991, 2014, 2016), and Canadian Dam Association (2013). Finally, the current and proposed legislation in Spain will be considered. Although, of course, only the current Spanish legislation has legal force in Spain, Proyecto Touro (2018a) has invoked the guidelines of the Canadian Dam Association (2013) in their responses to the concerns of Sociedade Galega de Historia Natural [Galician Natural History Society] and other organizations (Xefatura Territorial da Conselleria de Economia, Emprego e Industria, 2017), as well as in Proyecto Touro (2016). For context, Atalaya Mining, the owner of the Riotinto Mine, has exercised an option to acquire 10% of the share capital of Cobre San Rafael S.L. as part of an agreement that will enable Atalaya Mining to acquire up to 80% of Proyecto Touro, a proposed copper mine in Galicia, northern Spain (Atalaya Mining, 2019b).

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 classifications of hazard potential corresponds to an inflow design flood (FEMA, 2013). A dam with Low Hazard Potential must be designed for a 100-year flood (flood with a 1% exceedance probability in any given year) or “a smaller flood justified by rationale” (FEMA, 2013). A dam with Significant Hazard Potential should be designed for a 1,000-year flood (flood with an exceedance probability of 0.1% in any given year). However, a dam whose failure is expected to result in the loss of at least one life (High Hazard Potential) must be designed for the Probable Maximum Flood (PMF), which is defined as “the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study” (FEMA, 2013). The magnitude of the PMF is usually derived from the Probable Maximum Precipitation (PMP), which is defined as “the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year” (FEMA, 2013). It is worth noting that, according to the U.S. Army Corps of Engineers “the PMF does not incorporate a specific exceedance probability, but is generally thought to be well beyond the 10,000 year recurrence interval” (USACE-HCE, 2003).

In the same way, 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.” Just as with the design floods, “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, just as with the PMF, has emphasized that “there is no return period for the MCE” (USACE, 2016). 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%.

In terms of design floods, the safety guidelines for dams designed by the U.S. Army Corps of Engineers are, in some cases, even stricter than those recommended by FEMA (2013). For all dams designed or maintained by the U.S. Army Corps of Engineers, “APF [Annual Probability of Failure] ≥ 1 in 10,000 (0.0001) Per Year. Annual probability of failure in this range is unacceptable except in extraordinary circumstances” (USACE, 2014). The U.S. Army Corps of Engineers has four categories of dam safety standards, similar to the three hazard potentials of the Federal Emergency Management Agency. The strictest “Standard 1 applies to the design of dams capable of placing human life at risk or causing a
catastrophe, should they fail” (USACE, 1991). For this standard, “structural designs will be such that the dam will safely pass an IDF [Inflow Design Flood] computed from probable maximum precipitation (PMP) occurring over the watershed above the dam site.” For the third strictest Standard 3 dams, “the base safety standard will be met when a dam failure related to hydraulic capacity will result in no measurable increase in population at risk and a negligible increase in property damages over that which would have occurred if the dam had not failed” (USACE, 1991). For Standard 3 dams, “one-half of the PMF is the minimum acceptable IDF” (USACE, 1991).

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 flood and 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 flood or 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 flood should be 2/3 between the 1,000-year flood and the PMF, while 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 flood should be the PMF, while the design earthquake should be the 10,000-year earthquake or the MCE. There are many other guidelines for design floods in use worldwide and these were thoroughly reviewed by FEMA (2012).

The current dam safety legislation in Spain recognizes three categories of hazard potential (Agencia Estatal Boletín Oficial del Estado [State Agency Official State Bulletin], 1996; Ministerio de Medio Ambiente [Ministry of Environment], 1996). Category A “corresponde a las presas cuya rotura o funcionamiento incorrecto puede afectar gravemente a núcleos urbanos o servicios esenciales, o producir daños materiales o medioambientales muy importantes” [corresponds to dams for which rupture or malfunction could seriously affect urban centers or essential services, or cause very significant material or environmental damage] (Ministerio de Medio Ambiente, 1996). Category B “corresponde a las presas cuya rotura o funcionamiento incorrecto puede ocasionar daños materiales o medioambientales importantes o afectar a un reducido número de viviendas” [corresponds to dams for which rupture or malfunction could cause significant material or environmental damage or affect a small number of homes] (Ministerio de Medio Ambiente, 1996). Category C “corresponde a las presas cuya rotura o funcionamiento incorrecto puede producir daños materiales de moderada importancia y sólo incidentalmente pérdida de vidas humanas” [corresponds to dams for which rupture or malfunction could cause moderate material or environmental damage and only incidentally loss of human lives] (Ministerio de Medio Ambiente, 1996). Ministerio de Medio Ambiente (1996) further clarifies that an “urban center” requires as few as 50 inhabitants. On that basis, Category A roughly corresponds to High Hazard Potential (Federal Emergency Management Agency), Standard 1 (U.S. Army Corps of Engineers) and very high- or extreme-consequence dams (Canadian Dam Association).
The current dam safety legislation in Spain is less protective of the population, economic infrastructure and environment than in most of the developed world. Agencia Estatal Boletín Oficial del Estado (1996) distinguishes between the “avenida de proyecto” [project flood], which is the “máxima avenida que debe tenerse en cuenta para el dimensionado del aliviadero, los órganos de desagüe y las estructuras de disipación de energía, de forma que funcionen correctamente” [maximum flood that must be taken into account for the dimensioning of the spillway, the drainage structures and the energy dissipation structures in such a way that they function correctly] and the “avenida extrema” [extreme flood], which is “la mayor avenida que la presa puede soportar” [the largest flood that a dam can withstand]. Ministerio de Medio Ambiente (1996) then states, “En la actualidad, la avenida de proyecto es, en la mayor parte de los casos, la correspondiente a un período de retorno de 500 años” [At the present time, the project flood, in the majority of cases, corresponds to the 500-year flood]. The project flood seems to have the same return period (annual exceedance probability) independent of the consequences of dam failure. Moreover, Ministerio de Medio Ambiente (1996) does not state any return period or means of calculating the magnitude of the “extreme flood.” However, in the case of tailings dams, the project flood and extreme flood are not really different concepts, since there are few circumstances under which a tailings dam could survive the failure of the spillway. Although the dam safety legislation (Agencia Estatal Boletín Oficial del Estado, 1996; Ministerio de Medio Ambiente, 1996) does not discuss design earthquakes, the construction regulations (Ministerio de Fomento [Ministry of Development], 2009) classify dams in Categories A and B as civil works of “importancia especial” [special importance] that should be designed to withstand a 500-year earthquake.

The new proposed dam safety legislation aims to bring Spain up to date with the rest of the developed world (Ministerio para la Transición Ecológica [Ministry for Ecological Transition], 2018a-b). This legislation proposes return periods of 5000 years and 10,000 years for the “extreme flood” for earthen dams in Categories B and A, respectively (Ministerio para la Transición Ecológica, 2018b). For all dams in Category A, the “seísmo extremo” [extreme earthquake] would be the 5000-year earthquake in regions of low and moderate seismicity ($0.04g < a_b < 0.20g$) and the 10,000-year earthquake in areas of high seismicity ($a_b \geq 0.20g$) (Ministerio para la Transición Ecológica, 2018b), where $a_b$ is the seismic acceleration with 10% probability of exceedance in 50 years and $g$ is acceleration due to gravity. The above legislation would be quite similar to the guidelines of the Canadian Dam Association (2013), especially using its risk-informed approach. According to the seismic acceleration map found in Ministerio de Fomento (2009), the design acceleration for the location of the Riotinto Mine is $a_b = 0.07g$ (Golder Associates, 2016), so that the design earthquake for the tailings dams would be the 5000-year earthquake, according to the proposed legislation if the dams could be placed into either Categories A or B.
TAILINGS DAMS AT THE RIOTINTO MINE

*Description of Tailings Dams*

The tailings dams for the Aguzadera and Cobre reservoirs were constructed in three stages (Golder Associates, 2016). The first stage was the construction of starter dikes (also called cores) out of mine waste rock, 27 m high for the Aguzadera Dam and 35 m high for the Cobre Dam (see Figs. 8-9). (The heights vary due to the irregularity of the slate bedrock. All heights refer to the typical profiles shown in Figs. 8 and 9). As the space behind each starter dike filled with tailings, a second dike was constructed in the upstream direction. The construction material for the second dike was obtained by setting cyclones on the dam crest to remove the coarser fraction of tailings before the remaining tailings were discharged onto the reservoir. Contrary to the usual practice, the coarser tailings (sands) were not compacted before they were used to construct the second dike (Golder Associates, 2016). The sand dike is 44 m high for the Aguzadera Dam (see Fig. 8) and 41 m high for the Cobre Dam (see Fig. 9). The slopes of the sand dikes are 1V:2.6H and 1.3V:1H at
the interface between the dikes and the underlying tailings for the Aguzadera and Cobre Dams, respectively (see Figs. 8-9). These slopes are far steeper than the maximum of slope of 1V:4H that was recommended by Martin et al. (2002) for the prevention of static undrained failure. The third stage was the construction of a wall of mine waste rock on top of and downstream of the sand dike, which increased the dam heights by 5 m for the Aguzadera Dam (see Fig. 8) and 6 m for the Cobre Dam (see Fig. 9).

![Diagram](image)

**Figure 9.** The Cobre Dam was constructed using the upstream method (compare with Fig. 5a). Although the subsequent rock wall was constructed in the downstream direction, it does not change the essential feature that the uncompacted tailings are beneath the dam (labeled as sand). In fact, the sand that composes the dam was also never compacted (Golder Associates, 2016). The rock wall actually increases the probability of liquefaction by increasing the load on both the underlying dam and the underlying tailings. The inclination of the dam is too steep (1V:1.3H) and should be less than 1V:4H to prevent undrained shear failure (compare with Fig. 7). Atalaya Mining has proposed carrying out further raises of the dam to 405 masl using the upstream method (Ore Reserves Engineering, 2018). Dashed squares are 10 m on a side. Figure modified from Golder Associates (2016).

The Aguzadera and Cobre Dams are upstream tailings dams. The essential characteristic of upstream dams is that the dam is underlain by uncompacted tailings (compare Fig. 5a with Figs. 8-9). The emplacement of a rock wall on top of and downstream from the dam does not alter that essential characteristic. In fact, the overlying rock wall could increase the probability of liquefaction of the underlying tailings by increasing the load on the tailings and thus, the magnitude of a sudden consolidation of the tailings. However, the rock wall could also decrease the probability of liquefaction if it caused a slow consolidation of the underlying tailings. On the other hand, a non-uniform consolidation of the underlying tailings could affect the structural integrity of the rock wall because the tailings are the foundation for the rock wall (see Figs. 8-9). In this context, it should be recalled that the sand dikes were never compacted (Golder Associates, 2016),
so that liquefaction and non-uniform settlement of the sand dikes are also a matter of concern. I am not aware of any document that discusses the above issues. On the contrary, the English-language report to investors describes a plan to increase the height of the Cobre Dam by another 33 m using “waste mine rock fill by the upstream method” (Ore Reserves Engineering, 2018).

Figure 10. The perimetral canal isolates the Aguzadera tailings reservoir from the rest of the watershed (see Fig. 3) and was designed to accommodate the 500-year flood (corresponding to an annual exceedance probability of 0.2%). However, according to most international guidelines and the new proposed legislation in Spain, the entire reservoir system should be designed to withstand either the 10,000-year flood (annual exceedance probability of 0.01%) or the Probable Maximum Flood (significantly rarer than the 10,000-year flood). Even the design for the 500-year flood is questionable since the canal was more than half-full on at least two separate dates within four months in 2010 and 2011 (see Figs. 27a-b). Photo taken by author on June 20, 2019.
Figure 11. The stability of the tailings dams was evaluated across two profiles for the Aguzadera reservoir (A1 and A2) and one for the Cobre reservoir (C1). Red dots indicate positions of piezometers, while blue dots indicate drill locations for measurement of geotechnical properties. Figure modified from Golder Associates (2016).

The tailings are exported to the Aguzadera and Cobre deposits as a mixture of water and solid particles that is 35% solids by weight (Golder Associates, 2016). This is the conventional method of tailings delivery that does not involve any thickening (removal of water) from the tailings prior to storage in a tailings reservoir. These unthickened tailings
typically contain 20-40% solids, but the solids content can be as high as 60% (Klohn Crippen Berger, 2017). Thickening of the tailings before export to the reservoir can produce a high-density thickened tailings or a tailings paste with solids content of 60-75% by weight (Klohn Crippen Berger, 2017). Finally, tailings can be filtered before export so that they are 80% solids by weight and behave like a moist soil (Klohn Crippen Berger, 2017).

The Aguzadera and Cobre tailings deposits have been designed to withstand a 500-year flood. In particular, the perimetral canal that isolates the Aguzadera deposit from the rest of the watershed was designed to be able to carry the discharge from a 500-year flood (see Figs. 3 and 10; Golder Associates, 2016). This design safety criterion already sets the annual probability of dam failure due to flooding at 0.2%. Key operating criteria related to flooding are that the tailings beach must be at least 50 m wide at all times and the minimum freeboard (difference in height between the dam crest and the water level) must be 1.5 m (Golder Associates, 2016). However, no document has explained the above values in terms of ability to withstand a 500-year flood. Moreover, no document has explained the required beach width in terms of the ability of the dam to avoid failure after liquefaction (note the lack of any beach in Figs. 12a-c).

Figure 12a. Using the limit equilibrium method, Golder Associates (2016) calculated a factor of safety (FS) of FS = 1.9 for the Cobre Dam (profile C1; see Fig. 11). The factor of safety is the lowest ratio of available shear resistance to the activating shear forces along all potential surfaces of failure, so that FS = 1.0 is the point of failure. The factor of safety takes into account slope stability, but not possible failure due to static liquefaction, flooding or internal erosion. The calculation by Golder Associates (2016) is completely irrelevant, since it assumes a low water table (compare with the current water table in Fig. 21). Figure modified from Golder Associates (2016).
Figure 12b. Using the limit equilibrium method, Golder Associates (2016) calculated a factor of safety (FS) of FS = 1.8 for the Aguzadera Dam (profile A1; see Fig. 11). The factor of safety is the lowest ratio of available shear resistance to the activating shear forces along all potential surfaces of failure, so that FS = 1.0 is the point of failure. The factor of safety takes into account slope stability, but not possible failure due to static liquefaction, flooding or internal erosion. The calculation by Golder Associates (2016) is completely irrelevant, since it assumes a low water table (compare with the current water table in Fig. 21). Although Ramírez and Lain (2016) argued that the geotechnical properties of the tailings were irrelevant because failure surfaces would not intersect the tailings, the figure shows the most likely failure surface (base of the hatched region) to be well within the tailings. Figure modified from Golder Associates (2016).

The slope stability of the tailings dams was evaluated across two profiles for the Aguzadera reservoir and one for the Cobre reservoir (Golder Associates, 2016; see Fig. 11). These calculations were carried out using the limit equilibrium method and the input data were the geotechnical properties of the materials (measured at drill locations shown in Fig. 11) and an assumed height of the water table (see Figs. 12a-c). The water table was assumed to be at its historical high point, although the historical period was not specified (Golder Associates, 2016). Each slope stability calculation produced a factor of safety (FS), which is the lowest ratio of available shear resistance to the activating shear forces along all potential surfaces of failure, so that FS = 1.0 is the point of failure (slip condition). For each profile, factors of safety were calculated under the static condition (no seismic acceleration or liquefaction), under the acceleration of the 500-year earthquake, and under the condition of post-seismic liquefaction of the saturated tailings. For the static
condition, the factors of safety were $FS = 1.9$ for profile C1 across the Cobre Dam (see Figs. 11 and 12a), $FS = 1.8$ for profile A1 across the Aguzadera Dam (see Figs. 11 and 12b), and $FS = 2.0$ for profile A2 across the Aguzadera Dam (see Figs. 11 and 12c). These factors of safety are well above the minimum $FS = 1.4$ that is required by both the current and proposed Spanish legislation (Agencia Estatal Boletín Oficial del Estado, 2000; Ministerio para la Transición Ecológica, 2018) for dams in Categories A or B.

![Diagram](image)

**Figure 12c.** Using the limit equilibrium method, Golder Associates (2016) calculated a factor of safety (FS) of $FS = 2.0$ for the Aguzadera Dam (profile A2; see Fig. 11). The factor of safety is the lowest ratio of available shear resistance to the activating shear forces along all potential surfaces of failure, so that $FS = 1.0$ is the point of failure. The factor of safety takes into account slope stability, but not possible failure due to static liquefaction, flooding or internal erosion. The calculation by Golder Associates (2016) is completely irrelevant, since it assumes a low water table (compare with the current water table in Fig. 21). Although Ramírez and Lain (2016) argued that the geotechnical properties of the tailings were irrelevant because failure surfaces would not intersect the tailings, the figure shows the most likely failure surface (base of the hatched region) to be well within the tailings. Figure modified from Golder Associates (2016).

One of the objectives of this report is to estimate the probability of failure of the tailings dams, which is not the same concept as the factor of safety. The reason that the Spanish legislation requires $FS \geq 1.4$ instead of simply $FS \geq 1.0$ is that the factor of safety is based upon input data (geotechnical parameters and water table heights) that are imprecise and poorly-known (mostly due to the spatial variability of these data). Therefore, any calculation of $FS \geq 1.0$ includes a non-zero probability that the true value of the factor of safety (which would be obtained with a large quantity of precise data) is actually less than one. The basis of the Spanish legislation is the assumption that $FS \geq 1.4$ ensures that the probability that $FS < 1.0$ is sufficiently small. However, the calculated
factor of safety cannot be converted into a probability of failure without making further assumptions about the distribution of the input values. In fact, a well-constrained calculation of $FS = 1.2$ could reflect a smaller probability of failure than a calculation of $FS = 1.5$ with a great deal of uncertainty in the input values (Vick, 2002).

There is a more fundamental way in which a risk analysis, the objective of this report, is different from a slope stability analysis. A risk analysis considers all possible modes of failure, as well as the consequences of failure. A slope stability analysis considers only the tendency of a tailings dam to fail by sliding. The slope stability analysis does not take into account the possibility of failure by flooding, internal erosion, seismic liquefaction, static liquefaction or foundation failure. As discussed earlier, failure due to slope instability or sliding is not even one of the common causes of tailings dam failures. Although Golder Associates (2016) did calculate the factor of safety against slope instability following seismic liquefaction below the water table, that calculation did not address the likelihood of liquefaction. Finally, the limit equilibrium method is even more restrictive in considering only the possibility of fragments of the dam sliding over failure surfaces as rigid bodies. Many authors (e.g., Vick, 2002) have drawn attention to the overreliance on the analysis of only those failure modes (such as slope stability) for which analytical models and commercial software are available.
Figure 13. Cone penetration test (CPT) soundings evaluated the liquefaction susceptibility (tendency to contract after disturbance) in profile A2 (see Fig. 11) of the Aguzadera reservoir. On the left-hand side, CPT measurements were carried out to a depth of 37.2 m through the sand dike and the underlying tailings (see downstream drill location in Fig. 11). On the right-hand side, measurements were carried out to a depth of 30 m through the tailings immediately upstream from the sand dike (see Fig. 8 and upstream drill location in Fig. 11). Values of the critical state parameter $\Psi > -0.05$ (below and left of green curve) indicate contractile materials (susceptible to liquefaction). Golder Associates (2016) concluded “Se observan estériles de tratamiento con alta susceptibilidad a licuar (o experimentar una importante degradación de su resistencia... Arenas con comportamiento no 100% denso. Esto confirma la variabilidad esperada para este tipo de construcción aguas arriba con arena ciclonadas. Se observan intercalaciones de arenas más limosas con estado contractivo, las cuales serían susceptibles a experimentar licuación si están saturadas o bien, si su saturación es elevada (eventualmente mayor al 80%) [Tailings are observed with high susceptibility to liquefy (or experience a significant degradation of their resistance) ... Sands with not 100% dense behavior. This confirms the expected variability for this type of upstream construction with cycloned sand. Intercalations of siltier sands in a contractive state are observed, which would be susceptible to liquefaction if they are saturated or if their saturation is high (possibly greater than 80%)]. Figure modified from Golder Associates (2016).

Golder Associates (2016) did evaluate the susceptibility to liquefaction of the sand dam and the underlying tailings, which would be a part of evaluating the probability of failure due to liquefaction. Loosely-packed materials tend to contract after disturbance (and are called contractile materials) and are, thus, susceptible to liquefaction (see Fig. 6). On the other hand, densely-packed materials tend to dilate after disturbance (and are called dilatant materials) and are, thus, not susceptible to liquefaction. At the same drill locations (see Fig. 11), cone penetration test (CPT) soundings were carried out to evaluate the susceptibility to liquefaction. Fig. 13 shows the results for profile A2 of the Aguzadera reservoir. On the left-hand side, CPT measurements were carried out to a depth of 37.2 m through the sand dike and the underlying tailings. On the right-hand side, measurements were carried out to a depth of 30 m through the tailings immediately upstream from the sand dike (see Fig. 8). Values of the critical state parameter $\Psi > -0.05$ (below and left of green curve in Fig. 13) indicate contractile materials that are susceptible to liquefaction (Jefferies and Been, 2016). Golder Associates (2016) concluded “Se observan estériles de...
The last aspect of the tailings dams at the Riotinto Mine to consider here is the use of impermeable plastic sheets to lower the water table (Golder Associates, 2016). Impermeable plastic sheets (red line in Fig. 14) extend downward from the rock wall and 50 m in the upstream direction (the impermeable sheet is also visible in Fig. 23c). In Fig. 14, the upper water table (upper blue line) is the water table that would occur in the absence of the impermeable layer, while the lower water table that is the water table that results from the placement of the impermeable layer. Fig. 14 has been very influential and was sketched for the author at meetings with the Department of Mines of the Autonomous Community of Andalusia and the Province of Huelva. However, I am not aware of any document that actually calculates the position of the water table, so that the water table in Fig. 14 seems to be only a drawing. For example, the slope of the water table (which determines the elevation of emergence of seepage from the outer embankment of the dam) is set, not by the position of the impermeable sheet, but by the hydraulic conductivity of the materials on the downstream side of the impermeable sheet. As the hydraulic conductivity becomes higher, the slope of the water table becomes shallower, and the elevation of emergence of seepage becomes higher. However, I am not aware of any document that estimates or measures the hydraulic conductivity of the tailings or the dam materials. Finally, even the drawing of Fig. 14 is inconsistent with principles of upstream dam construction because saturated tailings should not be present underneath the dam (Martin et al., 2002). Other aspects of the tailings dams will be discussed in the Results section.
Figure 14. According to Golder Associates (2016), an impermeable layer (red line in figure) will force a lowering of the water table. The upper water table (upper blue line) is the water table that would occur in the absence of an impermeable layer. By comparison with the current water table (see Fig. 21), the impermeable layer is not working as intended. Figure modified from Golder Associates (2016).

Review by Ramírez and Laín (2016)

Ramírez and Lain (2016) reviewed the design and current condition of the tailings dams at the Riotinto Mine. The primary objective of their report was to answer the following question: Does it have any effect on dam safety whether the tailings are exported to the tailings reservoir with 35% solids or 50% solids by weight? Ramírez and Lain (2016) concluded that, “Usar lodos espesados al 50% no asegura que haya menos agua en las presas” [Using tailings thickened to 50% does not guarantee that there is less water in the dams]. The report by Ramírez and Lain (2016) was included as Appendix D in Golder Associates (2016) with the summary “También se considera por parte de Atalaya…el vertido de estériles de tratamiento a los depósitos con un contenido de sólidos en peso del 50%. Análisis adicionales muestran que su implementación no redunda necesariamente en una mejora de la seguridad de las presas ni en un incremento de la seguridad de la gestión de estériles de tratamiento, pudiéndose operar de forma igualmente segura descargando con el contenido de sólidos histórico de funcionamiento del proyecto de entre 32% a 35% de sólidos, por lo cual se propone por parte de Atalaya mantener la reanudación de los trabajos con dicho contenido de sólidos histórico, prescindiendo del espesamiento adicional mencionado. Este juicio técnico se respalda debidamente por instituciones revisoras calificadas para estos efectos, como la Escuela Técnica Superior de
Ingenieros de Minas y Energía de la Universidad Politécnica de Madrid...con resultado favorable, en cuanto a la validación de los argumentos presentados para asegurar el buen funcionamiento y la mantención de los factores de seguridad del proyecto original al descargar con un contenido de sólidos en torno al 34%" [It is also considered on the part of Atalaya ... the discharge of tailings to the reservoirs with a solids content 50% by weight. Additional analyses show that its implementation does not necessarily result in an improvement in the safety of the dams nor in an increase in the safety of the tailings management, being able to operate equally safely by discharging with the historical solids content of the operation of the project in the range 32% to 35% solids, for which it is proposed by Atalaya to maintain the resumption of work with the historical solids content, without additional thickening. This technical judgment is duly supported by reviewing institutions qualified for these purposes, such as the Higher Technical School of Mining and Energy Engineers of the Polytechnic University of Madrid...with favorable results, regarding the validation of the arguments presented to ensure proper functioning and the maintenance of the factors of safety of the original project when discharging with a solids content around 34%]. It is worth noting that the report was signed by Pedro Ramírez Oyanguren (Professor Emeritus) and Ricardo Laín Huerta (Professor) and that nothing indicated that Ramírez and Laín (2016) constituted an official opinion by the Polytechnic University of Madrid. It is curious that Appendix D of Golder Associates (2016) blacks out the names of the authors of the report.

Ramírez and Laín (2016) presented three arguments as to why the solids content of the tailings had no effect on dam safety. The first argument was that “todos los círculos críticos se encuentran dentro del muro (arena ciclonada)... Estos análisis confirman que la estabilidad de las presas está controlada principalmente por los materiales del muro y es poco sensible a la resistencia de las lamas” [All the critical circles occur within the wall (cycloned sand)....This analysis confirms that the stability of the dams is controlled principally by the materials of the wall and is not very sensitive to the resistance of the slimes] (Ramírez and Lain, 2016). The phrase “critical circle” refers to the potential failure surface that has the lowest factor of safety. These are the surfaces along which sliding will occur and are shown as the circular bases of the hatched regions in Figs. 12a-c. The software used to create Figs. 12a-c clearly assumes that all potential failure surfaces are portions of circles, although not all variations on the limit equilibrium method make that assumption. (It is clear that Golder Associates (2016) also used a 2-D version of the software that does not admit the possibility of slippage out of the plane of the profile (see Figs. 12a-c)). The critical circle is confined to the dam (sand and rock wall) for the Cobre Dam under the static condition (see Fig. 12a). However, the critical surface occurs well within the tailings under the static condition for both profiles of the Aguzadera Dam (see Figs. 12b-c). For all three profiles, the critical circles occur well within the tailings under the acceleration of the 500-year earthquake and under the condition of post-seismic liquefaction of the saturated tailings (Golder Associates, 2016). Therefore, the first argument is irrelevant because the premise is not true. Even if the premise were true, it is the geotechnical parameters of the tailings that force the critical circle to remain within the sand dike or the rock wall. Surely, the dam would not be stable if the tailings were replaced by air or water.

The second argument was that the quantity of water stored behind the tailings dams was controlled not by the quantity of water that was exported to the reservoir with
the tailings, but by the pumping of excess water from the Aguzadera and Cobre reservoirs to the Gossan reservoir. Ramírez and Lain (2016) reported under their list of observations from a field visit that, "El agua se recircula al 100 % y se introduce agua nueva para compensar la que se pierde por evaporación y la que contienen como agua intersticial los concentrados y los estériles. Dado que no existe espesador de colas, la propia balsa hace de espesador, por lo que el nivel de agua en la balsa depende principalmente de la recirculación que se haga" [The water is 100% recirculated and new water is introduced to compensate for what is lost by evaporation and what the concentrates and tailings contain as interstitial water. Given that there is no tailings thickener, the reservoir itself acts as a thickener, so that the level of water in the reservoir depends principally on the recirculation that occurs]. Clearly, the ability to use surface pumps to control the quantity of water in the reservoir assumes a rapid separation of solid particles and water (equivalent to a rapid consolidation of solid particles) or at least a separation rate that is independent of the initial water content of the tailings. This leads to the third argument of Ramírez and Lain (2016), which is that laboratory experiments by consultants for Atalaya Mining have demonstrated that tailings consolidation rates are independent of the initial solids content. These experiments and their interpretation will be considered in the Results section.

**Analysis of Consequences of Failure**

The analysis of the consequences of dam failure by Ayesa (2014) focused on the possible impacts on the city of Gibraleón (population 11,202), 78 km downstream from the tailings dams. However, the village of Sotiel Coronada (population 217) is only 40 km downstream from the tailings dams. Since an “urban center” requires only 50 inhabitants, a serious impact on the village of Sotiel Coronada should place the tailings dams at the Riotinto Mine into Category A, according to the existing Spanish dam safety legislation (Ministerio de Medio Ambiente, 1996). Moreover, any impacts on the mineworkers who could be immediately downstream from the dams at the time of failure should not be neglected.

Ayesa (2014) considered four possible scenarios for dam failure: (1) failure of the Cobre Dam that was not accompanied by flooding (2) failure of the Cobre Dam in combination with a 500-year flood (3) failure of the Aguzadera Dam that was not accompanied by flooding (4) failure of the Aguzadera Dam in combination with a 500-year flood. The possibility of a chain reaction involving Gossan Dam, Cobre Dam and Aguzadera Dam was not considered. Since the Aguzadera and Cobre dams are quite close and contain similar volumes of tailings, the predictions were not much different for failures of the two dams. Ayesa (2014) found that the tailings would arrive at Sotiel Coronada in about two hours if the failure occurred at the Cobre Dam, whether or not the dam failure was accompanied by flooding. The tailings would arrive at Sotiel Coronada in about three hours if the failure occurred at the Aguzadera Dam accompanied by flooding and in about two hours if a failure at the Aguzadera Dam was not accompanied by
flooding (see Fig. 15). The tailings were predicted to arrive in Gibraleón in more than five hours under all four scenarios.

The analysis of Ayesa (2014) was based on two critical assumptions besides those mentioned above. The first is that it was assumed that the volume of tailings that would be released following dam failure would be limited by an empirical formula based on data from 22 tailings dam failures (Rico et al., 2007)

\[ V_F = 0.354 \times V_T^{1.08} \]  

(1)

where \( V_F \) is the release volume and \( V_T \) is the total volume of stored tailings. In other words, only about 35% of the stored tailings would be released following dam failure. Eq. (1) has since been updated with more tailings dam failures by Larrauri and Lall (2018). The second assumption was that the time required to develop the breach in the dam is given by

\[ T = 4.8 \times V_F^{0.5} h \]  

(2)

where \( T \) is time in hours and \( h \) is the height of the dam above the downstream channel. The above assumptions will be critiqued in the Results section.
Figure 15. The existing analysis of the consequences of failure of the tailings dams at the Riotinto Mine showed that the tailings would arrive at the village of Sotiel Coronada (population 217; 40 km downstream) within two hours of failure of the Cobre Dam and in more than five hours at the city of Gibraleón (population 11,202; 78 km downstream) whether or not the failure was accompanied by a 500-year flood (Ayesa, 2014). It should be assumed that any mineworkers downstream of the dam would be impacted within seconds. Even so, the breach analysis underestimates the consequences of failure by neglecting the possibility of a chain breakage of all three dams, assuming a spillage of only 35% of the contents behind a single dam with no physical basis, and using an empirical formula for the time of breach formation that does not use data from tailings dams and which would be irrelevant for failure due to liquefaction. On the above basis, it should be assumed that failure of the dams would result in the loss of human life, so that the dams should be designed to withstand a 10,000-year flood or the Probable Maximum Flood, according to international guidelines and the new proposed legislation in Spain. Figure modified from Ayesa (2014).
METHODOLOGY

Based on the preceding review of tailings dams in general and of the tailings dams at the Riotinto Mine in particular, the objectives of this report can be subdivided into the following questions:
1) What is the probability of failure of the tailings dams by liquefaction?
2) Were Ramírez and Lain (2016) correct in asserting that the quantity of water stored behind the tailings dams was independent of the initial solids content of the tailings?
3) Do the tailings dams have an adequate beach?
4) What is the probability of failure of the tailings dams by internal erosion and flooding?
5) Did Ayesa (2014) adequately assess the consequences of failure of the tailings dams?

Figure 16. Although it is possible to walk safely on the Cobre tailings reservoir near the edge of the dam (see dam in background), this indicates only that the surface is dry. (By analogy, it is safe to walk on a frozen lake with an ice thickness of only 10 cm.) Alberto Lavandeira, CEO of Atalaya Mining, is on the left and Elena Solís, member of the Mining Group of Ecologistas en Acción, is on the right. Photo taken by the author on June 21, 2019.
The questions were addressed primarily by personal visits to the mine site during June 19-21, 2019, in the company of Elena Solís and Isidoro Ignacio Albarreal Núñez from Ecologistas en Acción [Ecologists in Action]. The visit on June 21 included six hours in the company of Alberto Lavandeira Adán, CEO of Atalaya Mining, and Enrique Delgado Palomo, Director General of Atalaya Mining. I also had a two-hour conversation with a former employee of the Riotinto Mine on June 28, 2019, and received 247 pages of analysis from the same person. The personal visits were supplemented by four key documents already mentioned, which were the most recent description of the tailings dams by Golder Associates (2016), the most recent dam safety evaluation by Ramírez and Laín (2016), the most recent dam breach analysis by Ayesa (2014), and the report to investors by Ore Reserves Engineering (2018). The preparation of this report also involved studying 1261 documents regarding the Riotinto Mine (too numerous to list), which did not substantially alter the conclusions reached from the personal visits and the four key documents.

Figure 17a. An excavation for geotechnical testing (A. Lavandeira, pers. comm.) at the edge of the Aguzadera Dam shows that the water table is almost at the surface immediately adjacent to the dam. Photo taken by the author on June 21, 2019.
RESULTS

Probability of Liquefaction

Having already established that the sand dam and the underlying tailings are contractile, or susceptible to liquefaction (Golder Associates, 2016; see Fig. 13), the next step in assessing the probability of liquefaction is a determination of the level of the water table within the tailings reservoir. Although it is possible to walk safely on the Cobre tailings reservoir near the edge of the dam (see dam in background in Fig. 16), this indicates only that the surface is dry. (By analogy, it is safe to walk on a frozen lake with an ice thickness of only 10 cm.) On the other hand, although the Aguazadera reservoir had received no tailings for 12 months at the time of the field visit (A. Lavandeira, pers. comm.), an excavation for geotechnical testing (A. Lavandeira, pers. comm.) at the edge of the Aguazadera Dam showed that the water table was almost at the surface immediately adjacent to the dam (see Fig. 17a). A view with minimal foreshortening from the top of the dam was used to estimate the depth of the water table in the excavation from the known height (1.5 m; Golder Associates, 2016) of a platform used for geotechnical testing (A. Lavandeira, pers. comm.). Since there was still some foreshortening, the depth to the water table of 2.9 m below the surface of the tailings was an underestimate (see Fig. 17b). Since groundwater flows down the slope of the water table toward the dam (the lowest elevation of the water table must be at the edge of the dam), the above observation indicates that the entire body of tailings in the Aguazadera reservoir is saturated, except for no more than the top three meters.
Figure 17b. A view with minimal foreshortening from the top of the dam was used to estimate the depth of the water table in the excavation from the known height (1.5 m; Golder Associates, 2016) of a platform used for geotechnical testing (A. Lavandeira, pers. comm.). Since there was still some foreshortening, the depth to the water table of 2.9 m below the surface of the tailings was an underestimate. Photo taken by the author on June 19, 2019.

The elevation at which seepage emerges from a dam is more important than the rate of seepage because it indicates the level of the water table within the dam. It has already been mentioned that, especially for upstream tailings dams, all seepage should exit the dam at the base of the starter dike (Martin et al., 2002; see Fig. 7). During the field visit, uncontrolled seepage was observed to occur through the bench of the rock wall of the Aguzadera Dam, 7.8 m below the top of the rock wall (compare with Fig. 8), indicating that almost the entire rock wall is saturated with water (see Figs. 18a-b). (Fig. 18a shows the drainage tubes for controlled seepage in addition to the uncontrolled seepage.) In fact, the most recent Google Earth image (July 16, 2013) shows numerous seepage sites along the outer embankment of the Aguzadera Dam (see Fig. 19). The same image even shows a “river” flowing from the settling pond to the seepage site, indicating a pathway for both rapid and prolonged seepage (see Fig. 19). The formation of a yellow precipitate (iron sulfate according to A. Lavandeira (pers. comm.)) at the seepage sites further indicates that the rock wall is almost completely saturated with water because oxidation occurs only after water exits the rock wall (see Figs. 20a-b).
Figure 18a. Uncontrolled seepage occurs through the bench of the rock wall of the Aguzadera Dam, 7.8 m below the top of the rock wall (compare with Fig. 8), indicating that almost the entire rock wall is saturated with water. Note drainage tubes (controlled seepage) in addition to the uncontrolled seepage. Photo taken by the author on June 20, 2019.

The observations that seepage is emerging at the upper bench of the rock wall (see Fig. 18a) and that the water table is 2.9 m below the surface of the tailings (see Fig. 17b) can be used to construct the level of the water table through the dam. The key constraint is that the elevation of seepage out of the rock wall cannot be higher than the water table behind the dam. Since the top of the sand dam is close to 3 m above the upper bench of the rock wall, the observations can be reconciled with the profile of the Aguzadera Dam (see Fig. 8) only if the current tailings level is at the level of the top of the sand dam (see Fig. 21). In fact, no sand dam was visible above the level of the tailings at any of the locations visited along the Aguzadera or Cobre Dams (see, for example, the view from the edge of the Cobre Dam in Fig. 23c). Fig. 21 clarifies that, out of the 70 m of tailings and the 44-m high sand dam, only the upper 3 m are not saturated with water. Since the top of the rock wall is 5 m above the top of the sand dam (see Figs. 8 and 21), only the upper 8 m of the rock wall are not saturated with water. A comparison of the current water table (see Fig. 21) with the relatively low water tables that were assumed for the slope stability analyses (see Fig. 12a-c) shows that all of the factors of safety that were calculated by Golder Associates (2016) are completely irrelevant to the current situation.
Figure 18b. Uncontrolled seepage occurs through the bench of the rock wall of the Aguzadera Dam, 7.8 m below the top of the rock wall (compare with Fig. 8), indicating that almost the entire rock wall is saturated with water. Photo taken by the author on June 21, 2019.

The current water table (see Fig. 21) can now be compared with the design water table (see Fig. 14), although note that Golder Associates (2016) showed the design water table only for the Cobre Dam and this report observed the water table only behind the Aguzadera Dam. A comparison of the figures implies that the impermeable sheet does not force a lowering of the water table, but that the groundwater within the reservoir is simply flowing immediately below the base of the impermeable sheet so that it emerges from the outer embankment of the dam at approximately the same elevation. This result would be consistent with a high hydraulic conductivity of the dam (sand dike and rock wall) materials, which has not been measured. The confinement of the groundwater by the impermeable sheet could suggest that, in some places, the groundwater is under artesian (greater than hydrostatic) pressure, which would increase the probability of static liquefaction. The numerical probability of dam failure by liquefaction will be considered further in the Discussion section.
Figure 19. Aerial photos and satellite images show numerous seepage sites along the outer embankment of the Aguzadera Dam (see Fig. 3 for location of figure). A “river” flows along the surface of the Aguzadera tailings reservoir from the settling pond to one of the seepage sites indicating a pathway for both rapid and prolonged seepage. Background is Google Earth image from July 16, 2013.

**Evaluation of Review by Ramírez and Lain (2016)**

It is now appropriate to reconsider the conclusion of Ramírez and Lain (2016) that the safety of the dams is not connected with the quantity of water that is discharged into the reservoirs. This conclusion was based on laboratory sedimentation tests that showed that “La densidad inicial de los estériles tiene escasa incidencia en el grado de densidad que adquieren una vez que quedan depositados en playas dentro del vaso, lo que se traduce en que las playas formadas cerca de los muros tendrán unas características muy similares cuando la descarga se efectúa con un 35% de sólidos o después de espesamiento adicional hasta el 50%. Ensayos de sedimentación realizados recientemente por EMED (2015) para niveles de espesamiento inicial de 30%, 35% y 40%, confirman esta afirmación ya que se observa que en todos los casos el estéril
depositado adquiere a las pocas horas una densidad de deposición similar, independiente de la dilución inicial de los lodos. El resultado de dichos ensayos de sedimentación es que pasadas las primeras 8 horas no hay una diferencia significativa en cuanto a densidad de estériles depositados que llega a un equivalente de 66-67% de sólidos...” [The initial density of the tailings has little impact on the degree of density that they acquire once they are deposited on the beaches inside the reservoir, which translates into the fact that the beaches formed near the walls will have very similar characteristics whether the discharge is made with 35% solids or after additional thickening up to 50%. Sedimentation tests carried out recently by EMED (2015) for initial thickening levels of 30%, 35% and 40%, confirm this statement since it is observed that in all cases the deposited tailings acquire a similar deposition density within a few hours, independent of the initial dilution of the tailings. The result of these sedimentation tests is that after the first 8 hours there is no significant difference in the density of deposited tailings that reaches an equivalent of 66-67% solids...] (Ramirez and Lain, 2016).

Figure 20a. The formation of a yellow precipitate (iron sulfate according to A. Lavandeira (pers. comm.)) at the seepage sites further indicates that the rock wall is almost completely saturated with water because oxidation occurs only after water exits the rock wall. Photo taken by the author on June 20, 2019.
Ramirez and Laín (2016) do not present graphs for the sedimentation test, but the relevant graph for the comparison of initial solids contents of 35% and 50% by weight appears in Golder and Associates (2016) (see Fig. 22a). This graph does not show equivalent densities that are independent of the initial solids contents after eight hours. In fact, this graph shows that the final solids contents are not independent of the initial solids content even after 240 hours (10 days) of sedimentation (see Fig. 22a). The reduction in final solids contents from 64% to 59% due to decreasing the initial solids content from 50% to 35%, respectively, is equivalent to increasing the total mass of water in the tailings reservoir by 24%.

Figure 20b. The formation of a yellow precipitate (iron sulfate according to A. Lavandeira (pers. comm.)) at the seepage sites further indicates that the rock wall is almost completely saturated with water because oxidation occurs only after water exits the rock wall. Photo taken by the author on June 21, 2019.
The relevant graph for the comparison of initial solids contents of 30%, 35% and 40% seems to appear in the report to investors by Ore Reserves Engineering (2018) with an ultimate source in a technical memorandum from Golder Associates dated July 31, 2015. The explanation from Ore Reserves Engineering (2018) was “Tailings settling tests were performed by laboratories in Spain. Laboratory results show that the solids compacted after 2 weeks reach about 67% solids, when settling slurries at 30 to 40% [initial solids content].” The graph is reproduced as Fig. 22b with no modifications. The labels “Axis Title” are simply the default settings in MS Excel. By analogy with Fig. 22a, the x-axis is probably time in hours, while the y-axis is probably final solids content as a percentage. However, it is unclear what point on the x-axis corresponds to “two weeks.” The graph does not show stabilization of solids contents because some sort of disturbance seems to have occurred between the last and next to last measurements. The horizontal lines on the far right-hand side of the graph do not indicate stabilization of solids contents because there are no data points on the far right-hand side (the horizontal lines are simply default settings). I am sorry to have to point out that these kinds of graphs and their misinterpretation draw into question the technical capacity of the consultants for Atalaya Mining.

Figure 21. The observations that seepage is emerging at the upper bench of the rock wall (see Fig. 18a) and that the water table is 2.9 m below the surface of the tailings (see Fig. 17b) can be reconciled with the profile of the Aguzadera Dam (see Fig. 8) only if the current tailings level is at the level of the dam of gossan sands. In fact, no sand dam is evident above the level of the tailings in either tailings reservoir (see photo of Cobre reservoir in Fig. 23c). The current water table indicates that nearly the entire dam and tailings are saturated with water. Figure modified from Golder Associates (2016).

Even more disturbing than these kinds of graphs and their misinterpretation is the reliance of Atalaya Mining upon a small number of laboratory experiments as a replacement for decades of field tests, industry experience, and guidelines for mining best practices that argue in favor of reducing the quantity of water that is exported to tailings.
reservoirs. In the first place, a laboratory sedimentation test is not equivalent to a field test because the laboratory test does not take into account the stirring that occurs in a tailings pond due to rainfall and repeated injection of tailings. In the second place, it is generally agreed that excess water increases the likelihood of all of the common causes of dam failure, excess water increases the consequences of dam failure by increasing the mobility of the tailings, and that the key to reducing both the number of dam failures and their consequences is thickening the tailings before they are exported to tailings reservoirs. For example, 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.”

Figure 22a. Ramírez and Lain (2016) used the above graph of a laboratory sedimentation test to argue that it was irrelevant for dam safety whether the tailings were exported to the tailings reservoirs with 35% solids or 50% solids. According to Ramírez and Lain (2016), “El resultado de dichos ensayos de sedimentación es que pasadas las primeras 8 horas no hay una diferencia significativa en cuanto a densidad de estériles depositados que a un equivalente de 66-67% de sólidos” [The result of these sedimentation tests is that after the first 8 hours there is no significant difference in the density of deposited tailings, being equivalent to 66-67% solids]. However, the graph shows that the final solids contents are not independent of the initial solids content even after 240 hours (10 days) of sedimentation. The reduction in final solids contents from 64% to 59% due to decreasing the initial solids content from 50% to 35%, respectively, is equivalent to increasing the total mass of water by 24%. A laboratory sedimentation test is not equivalent to a field test because the laboratory test does not take into account the stirring that occurs in a tailings pond due to rainfall and repeated injection of tailings. Finally, a single laboratory sedimentation test cannot be expected to overturn decades of field tests and industry practice that argue in favor of reducing the quantity of water that is exported to tailings reservoirs. Figure modified from Golder Associates (2016).
In their review of the cause of failure of the tailings dam at the Mt. 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) [with 80% solids contents] 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 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). The literature on this subject is too vast to review in this report. However, it is important to note that I am not aware of any reference (other than what has been produced by Atalaya Mining or their consultants) that argues that reduction of the water content of tailings is irrelevant because of the high sedimentation rate of tailings.
Figure 22b. Ore Reserves Engineering (2018) presented the above graph with the explanation, "Laboratory results show that the solids compacted after 2 weeks reach about 67% solids, when settling slurries at 30 to 40% [initial solids content]." The labels "Axis Title" are simply the default settings in MS Excel. By analogy with Fig. 22a, the x-axis is probably time in hours, while the y-axis is probably final solids content as a percentage. However, it is unclear what point on the x-axis corresponds to “two weeks.” The graph does not show stabilization of solids contents because some sort of disturbance seems to have occurred between the last and next to last measurements. The horizontal lines on the far right-hand side of the graph do not indicate stabilization of solids contents because there are no data points on the far right-hand side (the horizontal lines are simply default settings). This kind of graph and its misinterpretation draws into question the technical capacity of the consultants for Atalaya Mining.
Evaluation of Tailings Beach

Based on their field visit on April 28, 2016, Ramírez and Laín (2016) reported that “existe una playa mínima de 50 m de ancho en Aguzadera, entre el muro y el agua sobrenadante dentro de la presa, y mucho más grande en la presa de Cobre” [there exists a minimum beach of 50 m in width in Aguzadera and much larger in the Cobre Dam]. There was no indication that the width of the tailings beach was actually measured because Ramírez and Laín (2016) reported no methodology for measuring the beach width and included no maps, photos, satellite images, tables of measurements, or figures of any kind. In the same list of observations, Ramírez and Laín (2016) reported that “Según comunica la empresa, la situación actual de llenado de las presas de Cobre y Aguzadera, es de 1,7 Mm³, frente a una capacidad total de 3,7 Mm³, es decir, un 45% de su capacidad al inicio de la época estival” [According to the company, the current situation of filling the Cobre and Aguzadera Dams is 1.7 Mm³, compared to a total capacity of 3.7 Mm³, that is, 45% of its capacity at the beginning of the summer season]. The above quote is out of place in the report by Ramírez and Laín (2016) because a communication from the mining company does not belong in a list of observations by independent consultants. In any event, since the tailings beach must be maintained at a minimum width of 50 m (Golder Associates, 2016), and since the beach in the Aguzadera reservoir cannot be guaranteed (by actual measurements) to be wider than 50 m (Ramírez and Laín, 2016), it would be more accurate to say that the Aguzadera reservoir is already at 100% of its capacity. If the width of the tailings beach was not measured in the Cobre reservoir, then nothing can be said about its capacity to store more water.
Figure 23a. Desiccation cracks along the edge of Aguzadera Dam indicate that there is no tailings beach, but a mixture of sands and slimes (see close-up in Fig. 23b). For comparison, note the absence of desiccation cracks in the tailings beach at the Highland Valley Copper mine (see Fig. 4). The mixing of sands and slimes prevents the sand from draining and maintains the sands in a loosely-packed state, both of which promote liquefaction. Photo taken by the author on June 19, 2019.

At the time of the field visit of this report, no tailings beach was observed in either the Aguzadera or the Cobre reservoir. This means that there is no region of sand that is above water and that is visibly distinct from the region of water and slimes (see Fig. 4). For example, there are no desiccation cracks on the tailings beach at the Highland Valley Copper Mine (see Fig. 4) because cracking during drying is a property of silts and clays, not sands. On the other hand, well-developed desiccation cracks were visible in what should have been the tailings beaches along the edges of both the Aguzadera reservoir (which had not received tailings for 12 months; see Figs. 23a-b) and the Cobre reservoir (which was receiving tailings on a daily basis; see Figs. 23c-d). The above observation indicates that the tailings on the edges of the Aguzadera and Cobre Dams are not sands, but a mixture of sands and slimes.
Figure 23b. Desiccation cracks along the edge of Aguzadera Dam indicate that there is no tailings beach, but a mixture of sands and slimes (see far view in Fig. 23a). For comparison, note the absence of desiccation cracks in the tailings beach at the Highland Valley Copper mine (see Fig. 4). The mixing of sands and slimes prevents the sand from draining and maintains the sands in a loosely-packed state, both of which promote liquefaction. Photo taken by the author on June 20, 2019.

The mixing of sands and slimes in the tailings beach was the cause of the failure of the Fundão Dam at the Samarco Mine in Brazil in 2015 (Fundão Tailings Dam Review Panel, 2016). The presence of slimes between the sand particles impedes the drainage of tailings and increases the likelihood of liquefaction. In particular, the layering of sands and slimes was identified as the immediate cause of failure of the Fundão Dam by static liquefaction. This layering caused the layers of slimes to be squeezed outward (like toothpaste) between the layers of sands. As the sand layers were then pulled outward to conform to the motion of the slime layers, the sands were placed into an even more loosely-packed state, which made them even more susceptible to liquefaction. The trigger for static liquefaction was apparently a series of five small earthquakes with magnitudes in the range 1.8-2.6 (Fundão Tailings Dam Review Panel, 2016).
Figure 23c. Desiccation cracks along the edge of Cobre Dam indicate that there is no tailings beach, but a mixture of sands and slimes. For comparison, note the absence of desiccation cracks in the tailings beach at the Highland Valley Copper mine (see Fig. 4). The mixing of sands and slimes prevents the sand from draining and maintains the sands in a loosely-packed state, both of which promote liquefaction. Photo taken by the author on June 21, 2019.

In the case of the Cobre and Aguzadera reservoirs, the mixing of sands and slimes can be understood in terms of the way in which the tailings are discharged into the reservoirs. In the first place, the spigots (see Fig. 4) need to be sufficiently closely-spaced so that slimes are not deposited between the sand deposition cones of each spigot. For example, a Google Earth image from July 16, 2013, shows four sand deposition cones within 100 m in the Cobre reservoir on the edge of the common dam wall between the Aguzadera and Cobre reservoirs (see Fig. 24a). The placement of the sand deposition cones shows that the interval between spigots was 33 m in 2013. The sand deposition cones are barely intersecting, which is sufficient to prevent deposition of slimes between the spigots. On that basis, it is not clear how the formation of a uniform beach (without deposition of slimes between the spigots) can be achieved with the current interval between spigots of 50 m (Golder Associates, 2016). A possible explanation is that, previously, the coarser fraction of tailings was used to build the sand dams. At the present time, the dam is being constructed out of mine waste rock, so that the coarser fraction of tailings is discharged onto the tailings reservoir. It is possible that larger sand deposition
cones would result from injecting the coarser fraction of tailings onto the tailings reservoir. However, I am not aware of any document that shows that this idea was tested. Finally, the discussion by Ramírez and Lain (2016) regarding the plan “realizar un vertido directo o ‘spigotting’ con puntos de vertido cada 50 metros a lo largo de todo el perímetro de las presas y no sólo en extremos de los muros de las presas como se hacía en etapas anteriores” [to carry out a direct injection or “spigotting” with injection points every 50 meters along the entire perimeter of the dams and not only at the ends of the walls of the dams as in previous stages] [boldface added] cannot be reconciled with the image in Fig. 24a.

Figure 23d. Desiccation cracks along the edge of Cobre Dam indicate that there is no tailings beach, but a mixture of sands and slimes (note pen for scale). For comparison, note the absence of desiccation cracks in the tailings beach at the Highland Valley Copper mine (see Fig. 4). The mixing of sands and slimes prevents the sand from draining and maintains the sands in a loosely-packed state, both of which promote liquefaction. Photo taken by author on June 21, 2019.
At the current time, the tailings are not injected simultaneously through all of the spigots, but sequentially in sets of six spigots along a 250-m section of the dam (A. Lavandeira, pers. comm.; see Figs. 24b-c). It is possible that the sand deposition cones still intersect to prevent deposition of slimes between the spigots, but, as discussed above, it is not obvious that this occurs (see Fig. 24d). Even so, the problem is that, for each spigot, the region of slime deposition should be much larger than the cone of sand deposition. In Fig. 24d the region of slime deposition is arbitrarily drawn as a half-circle with diameter 325 m. Fig. 24d then demonstrates that sequential injection results in deposition of slimes on top of the sands that were deposited during the previous time interval, causing an eventual layering of sands and slimes instead of a tailings beach of sand.

Figure 24a. A Google Earth image from July 16, 2013, shows four sand deposition cones within 100 m in the Cobre reservoir on the edge of the common dam wall between the Aguzadera and Cobre reservoirs (see Fig. 3 for location of figure). The placement of the sand deposition cones shows that the interval between spigots was 33 m in 2013. The sand deposition cones are barely intersecting, which is sufficient to prevent deposition of slimes between the spigots. On that basis, it is not clear how the formation of a uniform beach (without deposition of slimes between the spigots) can be achieved with the current interval between spigots of 50 m (Golder Associates, 2016). It is possible that larger sand deposition cones would result from injecting the coarser fraction of tailings onto the tailings reservoir as opposed to using the coarser fraction to build the dam. However, I am not aware of any document that shows that this idea was tested. The discussion by Ramírez and Lain (2016) regarding a plan “realizar un vertido directo o ‘spigotting’ con puntos de vertido cada 50 metros a lo largo de todo el perímetro de las presas y no sólo en extremos de los muros de las presas como se en etapas anteriores” [to carry out a direct injection or “spigotting” with injection points every 50 meters along the entire perimeter of the dams and not only at the ends of the walls of the dams as in previous stages] [boldface added] cannot be reconciled with the above image.
**Probability of Internal Erosion and Flooding**

The appearance of red mud in the drainage tubes from the Aguzadera Dam is a worrying sign because it suggests the beginning of internal erosion of the dam (see Fig. 25a). The same red mud appears as the water is collected from the drainage tubes and pumped back into the Aguzadera reservoir (see Fig. 25b). Red mud is also visible in the uncontrolled seepage through the Aguzadera Dam (see Fig. 18b). Puddles of red mud on the foot of the outer embankment of the Cobre Dam are even visible in panoramic photos that are available on the website of Atalaya Mining (2019c) (see Figs. 26a-b). However, without further testing, it is not possible to determine whether the red mud consists of solid particles that were transported out of the dam by seepage or precipitates that formed after the seepage exited from the dam.

*Figure 24b.* Tailings are hydraulically injected into the Cobre reservoir through spigots that are arranged along the dam at 50-m intervals (spigot positions indicated by red labels). Tailings are not injected simultaneously, but sequentially in sets of six spigots along a 250-m section of the dam (A. Lavandeira, pers. comm.). Figure modified from Golder Associates (2016).
As already mentioned, the perimetral canal that isolates the Aguzadera reservoir from the rest of the watershed was designed to accommodate a 500-year flood. This standard is consistent with current dam safety legislation in Spain, but not with internationally recognized guidelines or the new proposed legislation in Spain. However, the ability of the current perimetral canal to accommodate even a 500-year flood might need reconsideration. The perimetral canal was more than half-full on at least two separate occasions within four months in 2010 and 2011 (see Figs. 27a-b). (Compare the photos in Fig. 10 and Fig. 27a, which were taken from almost the same location.) Moreover, note the sandbags in Fig. 27a, which indicate the expectation of higher water levels in the canal.

Figure 24c. Tailings are hydraulically injected into the Aguzadera reservoir through spigots that are arranged along the dam at 50-m intervals (spigot positions indicated by red labels). Tailings are not injected simultaneously, but sequentially in sets of six spigots along a 250-m section of the dam (A. Lavandeira, pers. comm.). Figure modified from Golder Associates (2016).
It should be clear that, in the case of the Riotinto Mine, the possibility of dam failure by static liquefaction is of much greater concern than the possibility of dam failure by internal erosion or flooding. However, not all dam failures result from a single cause and, in fact, there can be an interaction among the various modes of dam failure. For example, the loss of structural integrity due to internal erosion can cause a sudden consolidation of the tailings that would be a trigger for static liquefaction. The additional water pressure resulting from overtopping of the dam by the settling pond could be another trigger for static liquefaction of the dam. In light of the above, the possibilities of internal erosion or flooding should be regarded as contributing factors that increase the probability of failure by static liquefaction.

Figure 24d. The mixing of sands and slimes can be understood in terms of the sequential injection of tailings through sets of six spigots (with 50-m spacing) along a 250-m section of the dam (A. Lavandeira, pers. comm.). It is assumed that the sand deposition cones intersect to prevent deposition of slimes between the spigots, but it is not obvious that this occurs (see Fig. 24a). For each spigot, the region of slime deposition should be much larger than the cone of sand deposition and was arbitrarily drawn as a half-circle with diameter 325 m. The figure demonstrates that sequential injection results in deposition of slimes on top of the sands that were deposited during the previous time interval.
Evaluation of Analysis of Consequences of Failure

The analysis of the consequences of dam failure by Ayesa (2014) considered only the consequences of failure of either the Aguzadera Dam or the Cobre Dam, but not the possibility of a chain reaction that could even include the Gossam Dam (see Fig. 3). However, according to the “Guía para la elaboración de los planes de emergencia de presas” [Guide for the Preparation of Dam Emergency Plans], “Un escenario específico adicional a considerar se presenta en el caso en el que exista una sucesión de presas en el mismo río, en el que hipotéticamente se puede producir una rotura encadenada de presas (efecto dominó), en el que la rotura de una de las presas puede provocar las roturas de las presas aguas abajo” [An additional specific scenario for consideration presents itself in the case in which there exists a succession of dams on the same river, in which hypothetically a chain failure of dams could occur (domino effect), in which a failure of one of the dams could provoke the failures of the downstream dams] (Ministerio de Medio Ambiente, 2001). Ayesa (2014) explicitly recognized the existence of a succession of dams that could fail in a chain reaction by stating, “La presa de estériles para la deposición de los residuos de la explotación minera del PRT [Proyecto Riotinto], está constituida por tres secciones dispuestas en serie, Cobre, Aguzadera y Gossan, las cuales conforman en su conjunto una sola presa” [The tailings dam for the deposition of tailings by the PRT [Riotinto Project], consists of three sections arranged in series, Cobre, Aguzadera and Gossan, which together make up a single dam]. The above quote is even followed by an aerial photograph to show how the three dams could fail in a chain reaction (Ayesa, 2014). On that basis, the volume of water and tailings that would be released following a chain reaction failure of all three dams could be approximately three times the volume that would be released by failure of either the Aguzadera Dam or the Cobre Dam considered separately. (The total possible volume is only approximate because I have not found any document that states the volume of the Gossan reservoir.)
Figure 25a. Red mud in the drainage tubes from the Aguzadera Dam suggests the initiation of internal erosion. However, without further testing, it is not possible to determine whether the red mud consists of solid particles that were transported out of the dam by seepage or precipitates that formed after the seepage exited from the dam. Photo taken by the author on June 21, 2019.

Other questionable aspects of the analysis by Ayesa (2014) that would lead to an underestimation of the consequences of dam failure are the use of the empirical formulae given in Eqs. (1) and (2). Eq. (1) predicts the volume of the spill as a function of the total volume of tailings and water stored behind the dam based upon the past history of tailings dam failures. Although there is no physical basis for Eq. (1), it is still the most likely outcome of dam failure using statistical reasoning. However, the most likely outcome is not the worst-case scenario and consideration of the worst-case scenario is the explicit philosophy of both Ayesa (2014) and Ministerio de Medio Ambiente (2001). According to Ayesa (2014), “Si bien se admite la posibilidad de reducir o aumentar el número de escenarios, pero manteniendo siempre la obligatoriedad de tratar el correspondiente a la situación más desfavorable” [Although the possibility of reducing or increasing the number of scenarios is admitted, it is always necessary to analyze the scenario corresponding to the most unfavorable situation]. In this case, the most unfavorable situation would be the loss of all stored tailings and water, as occurred, for example, in the failure of the tailings dam at the Córrego do Feijão Mine in Brazil in 2019.
Figure 25b. Water from the drainage tubes (see Figs. 18a and 25a) is pumped back into the Aguzadera reservoir. Red mud in the recirculated water suggests the initiation of internal erosion. However, without further testing, it is not possible to determine whether the red mud consists of solid particles that were transported out of the dam by seepage or precipitates that formed after the seepage exited from the dam. Photo taken by the author on June 21, 2019.

The empirical formula given as Eq. (2) for the time required to form the breach in a dam is also a most-likely outcome, not a worst-case scenario. Clearly, the more slowly the breach forms, the lower will be the flow rate of tailings and water, the greater will be the time required for arrival of the tailings flood at a populated center, and the more dispersed the tailings flood will be in both space and time. Although no reference is given for Eq. (2), it is certainly based upon failures of earthen water-retention dams, not tailings dams, because I am not aware of any tailings dam failure for which the time of breach formation is known. Earthen water-retention dams and tailings dams are not strictly comparable because of their different materials and methods of construction. In general, breaches should form faster in tailings dams than in water-retention dams, since water-retention dams are constructed using natural materials chosen for their suitability, as opposed to available mining wastes (Vick, 1990). Moreover, although breaches take time to develop when dams fail by flooding or internal erosion, tailings dam failures by static liquefaction tend to be nearly instantaneous, being the only cases in which the time of breach formation is known. Based on the above, the true worst-case scenario would be an instantaneous failure of the tailings dam that would release all of the stored tailings and water.
The last questionable aspect of the analysis by Ayesa (2014) is the use of the 500-year flood as one of the scenarios. As already discussed, the appropriate worst-case scenario according to international guidelines and the new proposed legislation in Spain would be the failure of the tailings dams during a 10,000-year flood or the Probable Maximum Flood. Even under the assumptions used by Ayesa (2014), the tailings flood was predicted to arrive at Sotiel Coronada in one to two hours and at Gibraleón in five hours. Using more realistic assumptions for worst-case scenarios, as described above, should result in substantially lower arrival times. Therefore, without question, the tailings dams at the Riotinto Mine should be placed into the Category A of the current Spanish legislation (Agencia Estatal Boletín Oficial del Estado, 1996; Ministerio de Medio Ambiente, 1996) and the tailings dams should be regarded as if their failure would result in the loss of human lives. On that basis, according to the new proposed legislation on dam safety, the tailings dams should be designed to withstand the 10,000-year flood and the 5000-year earthquake.

Figure 26a. A panoramic view of the tailings reservoirs that is available on the website of Atalaya Mining (2019c) shows possible sites of internal erosion as puddles of red mud (see close-up in Fig. 26b). However, without further testing, it is not possible to determine whether the red mud consists of solid particles that were transported out of the dam by seepage or precipitates that formed after the seepage exited from the dam. Figure modified from Atalaya Mining (2019c).
Figure 26b. A panoramic view of the tailings reservoirs that is available on the website of Atalaya Mining (2018) shows possible sites of internal erosion as puddles of red mud (see far view in Fig. 26a). However, without further testing, it is not possible to determine whether the red mud consists of solid particles that were transported out of the dam by seepage or precipitates that formed after the seepage exited from the dam. Figure modified from Atalaya Mining (2019c).
DISCUSSION

Human Factors

Although the immediate cause of tailings dam failure is a physical phenomenon, such as a sudden consolidation of tailings, the root cause is always the actions of human beings. In a classic review of tailings dam failures, Davies (2002) wrote, “Consider the following Tailings Dam Failure Axiom - Tailings dam failures are a result of design, construction and/or operational management flaws - not ‘acts of god’”. On that basis, the human factors that either increase or decrease the probability of dam failure cannot be neglected. In this respect, the low technical capacity of some of the consultants for Atalaya Mining and the reliance of the mining company on those consultants has already been mentioned as a matter of concern.

The six-hour meeting among me, the CEO of Atalaya Mining, and the Director General of Atalaya Mining (as well as members of Ecologistas en Acción) was not only an excellent opportunity for me to learn about how the tailings dams were designed, constructed, and operated, but also to assess the technical capacity of the upper management of the mining company. Mr. Lavandeira and Mr. Delgado did not disagree with any of my observations, including the high water table immediately behind the dam, the seepage from the upper bench of the rock wall at the same elevation, the formation of precipitates of iron sulfate at the seepage sites, and the appearance of red mud in both the controlled and uncontrolled seepage. However, the upper management officers were unable to understand the observations in terms of the progression of the tailings dams toward failure by liquefaction and, at least at that meeting, were unwilling to learn. Inability or unwillingness to learn also falls into the category of low technical capacity.
Figure 27a. Although the perimetral canal (see Fig. 3) was designed to accommodate the 500-year flood (corresponding to an annual exceedance probability of 0.2%), it was more than half-full on at least two separate dates within four months in 2010 and 2011 (compare with nearby location in Fig. 10). The sandbags indicate an expectation of high water levels in the canal. Photo taken by an employee of the Riotinto Mine on March 26, 2011.
Numerical Probability of Dam Failure due to Liquefaction

The contributing factors that argue in favor of an assessment of a high probability of failure due to liquefaction of the tailings dams at the Riotinto Mine can be ranked as follows in terms of importance (1 = most important):
1) The entire Aguzadera tailings reservoir is saturated with water except for the upper three meters of the tailings and sand dam and the upper eight meters of the rock wall.
2) The sand dams and tailings in both the Cobre and the Aguzadera reservoirs are susceptible to liquefaction.
3) Neither the Cobre or the Aguzadera reservoirs have a tailings beach, but only an above-water mixture of sands and slimes.
4) Both the Cobre and Aguzadera Dams were constructed using the upstream method.
5) Atalaya Mining relies on consultants with a low technical capacity.
6) Atalaya Mining relies on a small number of laboratory experiments as a substitute for field tests, mining industry practice, and published industry guidelines.
7) The upper management of Atalaya Mining has a low technical capacity, including an unwillingness to learn from independent experts.
8) The tailings reservoirs were designed to accommodate only a 500-year flood.
9) The perimetral canal was over half-full on two separate dates within four months.
10) The appearance of red mud in both controlled and uncontrolled drainage suggests the beginning of internal erosion.
11) The tailings reservoirs were designed to withstand only a 500-year earthquake.

The above list of contributing factors essentially includes all of the steps that would be necessary for setting the stage for dam failure by liquefaction. The only step missing is the trigger that initiates the liquefaction process. That trigger would be an earthquake in the case of seismic liquefaction. The triggers for static liquefaction could come from a variety of sources, including the addition of more tailings, heavy rainfall or blasting. Of course, all of the stage-setting steps could be intensified. For example, the water table could rise even higher or the quantity of red mud in the seepage from the dams could increase even more. A comparison of Fig. 21 with Figs. 12b-c shows how quickly the water table in the Aguzadera reservoir has apparently risen over the last three years. As the stage-setting steps intensify, the magnitude of the trigger that is required to initiate the liquefaction event becomes progressively smaller. The intensification of the stage-setting steps must be also be understood in terms of the low technical capacity of the upper management of Atalaya Mining and their consultants, which makes it unlikely that the mining company will initiate corrective action that will reduce the probability of dam failure by liquefaction.

In summary, the assessment of the probability of dam failure by liquefaction is essentially the assessment of the probability of occurrence of a sufficient trigger. The best
judgement of this author is that the probability of dam failure due to liquefaction is 15% in any given year. This numerical value is roughly equivalent to an collective annual round of Russian roulette (a revolver with six chambers and one bullet) by the mineworkers and downstream residents of the Riotinto Mine. An annual probability of 15% corresponds to probability of dam failure of 28% over two years, 38% over three years, 48% over four years, and 56% over five years. In other words, there are even chances of dam failure over the next 4-5 years. The probability becomes 95% over the next 19 years, so that dam failure within the next 20 years is almost inevitable. The probability of dam failure does not necessarily decrease after mine closure. In fact, if the tailings dams are not adequately inspected and maintained in perpetuity, the annual probability of dam failure will increase accordingly.

**Figure 27b.** Although the perimetral canal (see Fig. 3) was designed to accommodate the 500-year flood (corresponding to an annual exceedance probability of 0.2%), it was more than half-full on at least two separate dates within four months in 2010 and 2011 (compare with Fig. 10). Photo taken by an employee of the Riotinto Mine on December 19, 2010.
CONCLUSIONS

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

1) Although rock walls have been constructed on top of and downstream from the sand tailings dams at the Riotinto Mine, the tailings dams are still upstream dams because uncompacted tailings are underneath the dam.

2) Although the Aguzadera reservoir has received no tailings for 12 months, the water table directly behind the dam is only 2.9 meters below the surface, while uncontrolled seepage occurs through the downstream embankment at the same elevation, indicating that the tailings, the sand dam, and the overlying rock wall are still nearly completely saturated with water. The saturated state of the dam is further indicated by the precipitation of iron sulfate in the seepage from the dam.

3) Although a wide beach of tailings sand is required to prevent dam failure due to both flooding and liquefaction, the pronounced desiccation cracks behind the dam indicate a mixing of sands and slimes, so that the beaches are non-existent. The mixing of sands and slimes promotes static liquefaction by preventing drainage of the sands and maintaining the sands in an unconsolidated state.

4) The analysis of geotechnical tests using the critical state method has been used to show that the both the tailings and sand dam are contractile, or susceptible to liquefaction.

5) Although existing stability analyses indicate a high factor of safety, they are irrelevant because they assume a low water table.

6) The dams were designed to withstand a 500-year flood, which is not consistent with international standards and proposed changes to Spanish legislation that would require designs to withstand the 10,000-year flood or the Probable Maximum Flood.

7) The appearance of red mud in both the controlled seepage (drainage tubes) and uncontrolled seepage suggests the beginning of internal erosion of the dams.

8) The failure to thicken the tailings before storage has been justified by misinterpreted laboratory sedimentation tests and is inconsistent with current industry practice.

9) Based on the above, the probability of dam failure due to liquefaction has been assessed at 15% in any given year.

10) The existing analysis of the consequences of failure is an underestimate in that it neglects the possibility of a chain breakage of all three dams, neglects the impacts on mineworkers and on the village of Sotiel Coronada (40 kilometers downstream), assumes a spillage of only 35% of the contents behind a single dam, and uses an empirical formula for the time of breach formation that does not use data from tailings dams and which would be irrelevant for failure due to liquefaction.
RECOMMENDATIONS

The recommendations of this report can be summarized as follows in order of implementation (1 = immediate implementation):

1) There should be an immediate cessation to the introduction of more tailings and water to the reservoirs at the Riotinto Mine.
2) Emergency plans should be developed and implemented for the downstream communities, especially for the communities of Sotiel Coronada and Gibraleón. This is not meant to imply that evacuation of these communities is necessary, but that alert systems, publication of evacuation routes, and other aspects of emergency response should be put into place.
3) Plans should be developed and implemented for the drainage of water from the Aguzadera and Cobre reservoirs and other measures that are deemed necessary to reduce the probability of dam failure. These plans should be reviewed by a team of independent experts prior to implementation. A critical aspect of these plans will be the treatment of the drainage water before it is released into the environment.

ACKNOWLEDGEMENTS

I am grateful to Alberto Lavandeira Adán, CEO of Atalaya Mining, and Enrique Delgado Palomo, Director General of Atalaya Mining, for the six hours that they devoted to me on June 21, 2019. I am grateful to Elena Solís and Isidoro Ignacio Albarreal Núñez from Ecologistas en Acción for arranging the logistics of the visits to the Riotinto Mine. Finally, thanks are due to a former employee of the Riotinto Mine for his analysis and the photos in Figs. 27a-b.

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RISK ANALYSIS OF THE TAILINGS DAMS AT THE RIOTINTO MINE, ANDALUSIA, SPAIN