K4.27 SPILL RISK

A REVIEW OF RECENT TAILINGS DAM FAILURES, DAM FAILURE MODELS, AND THEIR RELEVANCE TO THE APPLICANT'S PROPOSED BULK TSF DESIGN

Numerous public comments were received on the Draft Environmental Impact Statement (DEIS) requesting analysis of a full tailings dam failure to be included in the Environmental Impact Statement (EIS). Commenters cited historic tailings dam failures at various locales around the world, particularly recent tailings dam failures in British Columbia (Mount Polley 2014) and Brazil (Fundão 2015; Feijão 2019), and expressed concern that similar failures could occur at the Pebble mine. Commenters were specifically concerned about the potential for adverse impacts to downstream ecosystems, as have occurred from historic failures.

Many commenters cited results from recent tailings dam failure models produced by the US Environmental Protection Agency (EPA) in the Bristol Bay Watershed Assessment (EPA 2014) and by the Nature Conservancy (Lynker 2019), which were based on a hypothetical mine at the site of the Pebble mine. These models predicted extensive downstream inundation with high volumes of tailings and fluid released in the event of catastrophic dam failures. These models were intended to model failures from the Applicant's mine, but did not take into account details of the design of the bulk Tailings Storage Facility (TSF), including the use of thickened tailings, water removal plans, dry closure design, and other features described below. Rather, the models assumed the release occurred from a water-inundated TSF, and based their release volume results on historic failure data that are not relevant to the proposed Pebble mine.

Commenters expressed concern over failures at both the bulk TSF and the pyritic TSF. Most comments, however, were focused on the bulk TSF, as it is the largest facility, and would exist in perpetuity. The pyritic TSF would exist only during and shortly after active mine operations, and would then be removed, with pyritic tailings pumped into the open pit for permanent subaqueous storage. The EPA and Lynker failure models also focused on the bulk TSF that would exist in perpetuity. Therefore, this review on tailings dam failure and hypothetical modeling relevance with respect to the mine is focused on the bulk TSF.

K4.27.1 Purpose

This review is intended to: 1) review commonalities of historic TSFs that have experienced failure; 2) provide details on the design of the proposed bulk TSF in comparison with historic TSFs that experienced failure; 3) provide a review of recent tailings dam failures that have occurred since 2014, in context of how those facilities compare with the proposed bulk TSF; and 4) review the tailings dam failure models put forth by EPA and Lynker to note how they are or are not relevant to the Applicant's proposed project.

K4.27.1.1 Historic Tailings Dam Failures

There is a history of catastrophic tailings dam failures around the globe. Some of these failures have been devastating, causing loss of life, adverse impacts to downstream environments, and property damage. The most damaging dam failures involve a large release of fluid, and tailings that are mobilized with the fluid or entrained in the fluid.

Most significant historic tailings dam failures have some commonalities: 1) most large failures were from traditional "lagoon" type TSFs that typically had much of their surface inundated with water; 2) most of the stored tailings were discharged into the TSF as conventional or water-rich slurries; and 3) most of the dams that have failed historically were raised by upstream dam construction methods.

Water-inundated Tailings Storage Facilities

Many types of mine tailings are categorized as potentially acid generating (PAG). These tailings contain significant amounts of sulfur, which, when exposed to oxygen, can produce sulfuric acid. Sulfuric acid can be harmful to the environment. PAG tailings have therefore been traditionally stored in subaqueous conditions, in TSFs that are under a constant water cover, often referred to as tailings "lakes" or "lagoons." This constant water cover cuts off the oxygen supply to tailings, and thereby reduces or eliminates the ability of the tailings to generate acid, thereby protecting downstream environments.

The presence of a full water cover on top of a TSF, however, increases the potential severity of a tailings release. When large amounts of water are present during a dam failure, the tailings are subject to "erosion," wherein the water which flows out of the TSF erodes or mobilizes solid tailings particles as it flows; and/or to "static liquefaction," wherein the tailings mass liquefies because of the high content of water contained in the tailings. The mobilized tailings can be carried, or entrained, by the flowing water, and the flow becomes a slurry of water and tailings. A water-rich release can entrain significant amounts of tailings, such that many historic releases drained large amounts of the stored tailings, which flowed out of the TSFs as slurries.

Some tailings are not PAG, and do not require subaqueous storage. These tailings can be stored under comparatively dry conditions. (The extreme case of this is the storage of "filtered" or "dry stack" tailings.) The absence of a water cover over the tailings reduces the probability of a tailings dam failure, and reduces the potential severity of a release. In the event of a dam failure, without a large amount of water present to mobilize the tailings, fewer tailings would be entrained and able to flow out of the facility, such that tailings release volumes and travel distances would be limited.

The Applicant's mine site design includes two TSFs. The pyritic TSF would be a water-inundated "lagoon" type TSF required to store the PAG/pyritic tailings subaqueously during operations. These tailings would be relocated from the pyritic TSF shortly after the close of mining and placed in the open pit for perpetual subaqueous storage.

The other TSF would be the bulk TSF. Bulk tailings would not require subaqueous storage, so the bulk TSF would not have a full water cover, but would have only a small supernatant pond during operations. At the end of operations, the bulk TSF would be put into "dry" closure, with no supernatant pond, and would remain as a landform in perpetuity. See "Applicant's Bulk TSF Design" below.

Tailings Slurries

Historic mines have generally disposed of tailings into TSFs by adding water to the tailings to create tailings "slurries" that can be pumped through pipelines into a TSF for storage. Tailings slurries typically contain 65 to 80 percent water, and the remainder tailings solids. Because of these high water contents, tailings slurries have low viscosity; or low resistance to flow. Such fluid slurries held in TSFs are generally poorly consolidated and are therefore more susceptible to erosion, static liquefaction, and liquid flow in the event of a dam breach. Tailings slurries can exhibit fluid behavior and readily flow like water (MEND 2017). Most historic failures have occurred from TSFs that accept and store tailings slurries.

The Applicant would not be using tailings slurries, but would use "thickened" tailings, which have a lower water content than slurries. Thickened tailings cannot flow as easily as slurry tailings because there is less water to mobilize them. See "Applicant's Bulk TSF Design" below.

Upstream Dams versus Downstream and Centerline Dams

Tailings dams, often called embankments, may be constructed and sequentially raised by various methods, including upstream, downstream, or centerline methods (as well as modifications of these methods). Upstream dams are the most common, and are sequentially raised by placement of fill on top of stored tailings in the upstream direction. Downstream dams are raised in the downstream direction by placing fill on top of the dam crest and downstream slope of the previous raise. Centerline construction is a method in which a dam is raised by concurrently placing fill on top of the dam crest; the upstream slope, including portions of the tailings beach; and the downstream slope of the previous raise. Centerline dam raises are built mostly on top of fill material from the previous raise, and partly on top of tailings adjacent to the dam.

Upstream dams are generally considered less stable than downstream or centerline dams because the dam raises are built on top of tailings. When these tailings are fluid-saturated, they can be especially weak and susceptible to static liquefaction and liquid flow in the event of a dam breach. Upstream dams require the least amount of fill material to construct, and are the least expensive type of dam. Most historic failures have been from dams built by upstream construction methods.

The Applicant would construct the bulk TSF embankments by downstream and centerline methods, not the upstream method. The main embankment would be raised by the centerline method, and the south embankment would be raised by the downstream method. See "Applicant's Bulk TSF Design" below.

K4.27.1.2 The Industry Call for Water Reduction in Tailings Storage Facilities

There is widespread awareness across the mining industry that excess fluid stored with tailings increases the risk of tailings releases. In particular, since the 2014 Mount Polley dam failure, there has been a call within the mining industry to reduce the amount of water held on top of TSFs and within the tailings (interstitial, or pore water) to promote stability of the stored tailings. Best available technology (BAT) principles suggested following the Mount Polley dam failure (Morgenstern et al. 2015) include eliminating or minimizing surface water in TSFs and promoting unsaturated conditions in tailings through drainage provisions.

When a flood of surface water spills from a TSF, the water erodes, or entrains, the tailings beneath, so that the release becomes a slurry of tailings-rich fluid. This flood of tailings slurry can mobilize very high volumes of solid tailings. When there is no water cover or supernatant pond present on top of the tailings, it eliminates the chance of a flood of a large volume of water, and also reduces the ability of the stored tailings to be mobilized out of the TSF.

Providing drainage in the TSF allows excess pore fluid to drain out of the tailings, so that less water is held in the pore space, and tailings remain less saturated. Less-saturated tailings are less susceptible to static liquefaction, and would therefore not be able to mobilize and flow as easily in the event of a dam breach. Therefore, promoting unsaturated conditions in the tailings through drainage provisions reduces the chances of a major release of tailings.

Another technology that aims to reduce the amount of water held in TSFs is the use of "thickened tailings." Tailings have long been transported into TSFs via pipelines in the form of "tailings slurries," which typically contain 65 to 80 percent water, and the remainder tailings solids. Thickened tailings, in contrast, have only 40 to 50 percent water. The use of thickened tailings rather than tailings slurries introduces significantly less water into a TSF.

The Mount Polley Independent Expert Engineering Investigation and Review Panel (IEEIRP) also stated that placing tailings in mined-out open pits is the most direct way to reduce the number of TSFs subject to failure (Morgenstern et al. 2015). The Applicant has proposed this for pyritic TSF.

This was also considered for the bulk TSF as part of the National Environmental Policy Act (NEPA) Alternatives Analysis (Appendix B), but was ruled out as not practicable for the Pebble Project.

The Mount Polley IEEIRP also stated that “surface storage using filtered tailings technology is a prime candidate for BAT” (Morgenstern, et al. 2015). This alternative of filtered tailings (also called dry stack tailings) was also put forth for consideration as part of the NEPA Alternatives Analysis process (Appendix B). However, dry stack/filtered tailings were considered not practicable for the Pebble Project.

The BAT objective of reducing water in the tailings could also be achieved by compacting tailings to drive out excess fluid from the pore spaces between the tailings particles, and reduce the ability of tailings to flow in the event of a dam failure. Luino and De Graff (2012) conclude that tailings that are deposited as a slurry and not able to drain their excess fluid will tend to maintain a state of saturation under their self weight. This would result in limited additional consolidation over time and the continuation of a lower tailings density. Tailings can be mechanically compacted, which is generally not feasible for slurry or thickened tailings, but is routinely performed on dry stack tailings. Compaction of tailings is considered not practical for the bulk TSF.

K4.27.2 Applicant’s Bulk Tailings Storage Facility Design

The Applicant has proposed a design for the bulk TSF that would minimize surface water storage above the tailings and promote unsaturated, or dryer, conditions in the bulk tailings through drainage provisions. The Applicant would also use thickened tailings, which would reduce the amount of fluid that is actually introduced into the TSF to start with.

The Applicant’s bulk TSF design is different than that of most other historic and current TSFs. The proposed design is especially distinct when compared to most historic mines that have experience large failures. Some of these differences are:

1. Separate tailings streams and TSFs for the bulk tailings and pyritic tailings. This is in contrast to mines with one TSF for all the tailings combined, which often have a full water cover.
2. Bulk TSF main embankment starter dams fully founded directly on bedrock and not on soil. This is in contrast to mines with TSF embankments built on top of soil, or, in some cases, on top of saturated tailings, that provide weaker embankment foundations than bedrock.
3. Centerline and downstream embankment construction above the starter dam, versus upstream dam construction above the starter dam, to provide increased stability of the embankments. This is in contrast to mines with upstream construction raises over the stored tailings, which are inherently less stable than centerline raise embankments.
4. Discharge of thickened tailings to the bulk TSF at 55 percent solids content by weight, versus slurry tailings disposal of 20 to 30 percent solids, such that the stored tailings would contain a third to a half of the water that a conventional slurry would contain. This is in contrast to mines that use slurried tailings that would contain two to three times the amount of water than thickened tailings would contain.
5. Bulk TSF design based on flow-through seepage out of the main embankment to control the water in the tailings, such that the water level in the tailings (the phreatic surface) would be lowered near the main embankment, in order to improve the embankment stability. This is in contrast to mines that have higher water levels (phreatic surfaces) near the embankments, and therefore lower embankment stability.

6. Minimal supernatant pond size on the bulk TSF tailings surface. Surface water from the TSF would be continually removed and pumped to the main water management pond (main WMP), which would be sized sufficiently to always receive and store excess surface water from the TSF. This would reduce the amount of water in the TSF so that it can operate as a TSF, and not as a water storage reservoir, and to eliminate the risk of overtopping. This is in contrast to mines with large TSF supernatant ponds or full water covers and no means of storing this water elsewhere, such that the TSFs need to be operated as water storage reservoirs, which they may not be designed to do.
7. Bulk TSF would be put into “dry closure,” the tailings would be contoured and ultimately converted into a permanent landform with no water ponded on the surface. This is in contrast to mines with permanent water covers over the TSFs.

K4.27.2.1 Separate Bulk and Pyritic Tailings Storage Facilities

Most hard rock mining operations have tailings with some level of a pyritic/PAG component, so that subaqueous storage of tailings is required to reduce the potential for ARD. There is added expense in separating PAG tailings from non-PAG tailings, so most mines keep all the tailings together and store them in one TSF with a water cover.

The Applicant’s design is distinct from most mine sites, in that it would separate bulk tailings from pyritic/PAG tailings. This design would serve to minimize the volume of tailings that require subaqueous storage.

Based on extensive analysis of rock samples from the site, 88 percent of tailings would be bulk tailings. Bulk tailings are chemically distinct from pyritic/PAG tailings, in that they do not have a significant PAG component, and therefore do not require subaqueous storage. (Although because the process of tailings separation is inherently imperfect, the bulk tailings would likely have a small PAG component.)

The remaining 12 percent of tailings would be PAG/pyritic tailings, which would require perpetual subaqueous storage to reduce the potential for acid rock drainage (ARD). Pyritic tailings would be stored in a separate full water cover-type TSF during operations, and then relocated to the open pit soon after the close of mining operations. The open pit would be allowed to fill with water during closure/post-closure, which would maintain the pyritic tailings in subaqueous storage in perpetuity.

K4.27.2.2 Embankment Foundations on Bedrock, not on Overburden

The bulk TSF main embankment starter dam would be constructed directly on top of bedrock, and not on soil/overburden, as advocated by Morgenstern (2018). A bedrock foundation would provide the dam with greater stability than that of a soil foundation, especially a soil profile with loose, unconsolidated materials that may not be detected during geotechnical investigations. See Section 4.15, Geohazards and Seismic Conditions, for further details on the embankment foundation.

K4.27.2.3 Centerline and Downstream Dams versus Upstream Dams

Most historic mine failures have been from upstream dams, which are known to be less stable than downstream or centerline dams. Rico et. al. (2007a) estimated that 76 percent of global TSF failures involved upstream dams. Many of the upstream dams failed because of overtopping and/or weak soils, or saturated tailings under the dams and the upstream raises.

is intended to promote unsaturated conditions in the coarse tailings deposited near the embankment and reduce porewater pressures in the embankment fill materials.

Modeling results suggest that based on this design, the phreatic surface adjacent to the main embankment would be lowered (although uncertainty remains as to what the actual phreatic surface depths would be). Large, continuous, engineered filter zones in the embankment would be designed to promote internal drainage and reduce the phreatic surface, which would enhance stability.

Based on the Applicant design of the bulk TSF, the only standing water above the tailings in the TSF would be a relatively small supernatant pond near the center of the TSF, away from the main and south dams. Tailings "beaches" would surround the pond and would not be inundated with water (see Figure 2-66). The uppermost tailings of the beaches, based on the design, would be relatively well-drained; that is, not fluid-saturated. The maintenance of a minimal supernatant pond and lack of surface water cover over the tailings would be critical to the success of the TSF design.

Drainage Provisions

The bulk TSF would include basin and embankment underdrains to help maintain a reduced phreatic surface in both the tailings and in the embankment. Underdrains would be used in natural tributary drainages beneath the TSF, and an aggregate drain at a topographic low point beneath the main embankment to provide a preferential seepage path from the tailings to downstream of the embankment toe. Additional underdrains running parallel to the main embankment would allow for drainage of seepage collected along the embankment.

Water would then be able to seep downward beneath the TSF and be collected in the seepage collection system, reducing the amount of fluid held in the TSF. Drainage provisions would be intended to promote unsaturated conditions, but the phreatic surface could remain higher throughout mine operations, as discussed above. Piezometers would be used in the TSF to monitor the phreatic surface levels. Adequate drainage would be critical to the success of the bulk TSF design. If required to achieve drainage goals, alternative drainage-enhancing features would be considered, such as vertical or horizontal drains (PLP 2019-RFI 130; described in Chapter 5, Mitigation).

As described above, the only standing water above the tailings in the TSF would be a relatively small supernatant pond near the center of the TSF, away from the main and south embankments. Tailings beaches would surround the pond and would not be inundated with water (see Figure 2-66). The uppermost tailings of the beaches, based on the design, would be coarser, and therefore would drain better so they would not be saturated. The flow-through concept would allow water to percolate downward through the tailings. Deeper tailings would be fluid-saturated, below the phreatic surface. See Figure K4.15-3 for a cross-section of the estimated phreatic surface.

A seepage analysis was conducted of the bulk TSF based on a two-dimensional (2D) model (SEEP/W) that predicted seepage rates for use in the site-wide water balance model (Section 4.16, Surface Water Hydrology). The analysis provides information on the behavior of the phreatic surface in the TSF. During operations, the phreatic surface would vary based on the tailings discharge spigot locations around the TSF perimeter. The seepage model also shows that the phreatic surface would be expected to decline in early closure after the tailings discharge ceases (PLP 2019-RFI 006b, 008h, 130). Details of the seepage model assumptions, input parameters, material layout, boundary conditions, and results are provided in Appendix K4.15. Figure 10 in RFI 109e also shows the predicted phreatic surface in the bulk TSF based on additional 3D groundwater modeling (see Section 4.17, Groundwater Hydrology).

There are several examples of centerline dams worldwide that are directly comparable in design, height, and seepage rate to the bulk TSF main embankment, and are operating successfully. The Constancia Mine tailings dam in Peru, owned by Hudbay Minerals, is a zoned rockfill dam with a vertical clay core, and is greater than 328 feet high. The Highland Valley Mine H-H tailings dam in British Columbia, owned by Teck Resources, is an earthfill dam with a low-permeability vertical core, with random fill and tailings placed upstream, and variable waste fill on the downstream side, and is 318 feet high. The Yankee Doodle tailings dam at Continental Mine in Montana, owned by Montana Resources, is built of rockfill and is 750 feet high with alluvial soils placed over the upstream slope as a filter between the tailings and rockfill to reduce the potential of tailings piping through the embankment. These three dams have similar configurations and materials as planned for the bulk TSF main embankment, but only the Yankee Doodle Dam can be considered to be a flow-through embankment. The Constancia and Highland Valley H-H dams are not flow-through dams because of the presence of the vertical cores. The engineered filter zone in the bulk TSF, consisting of graded sands and gravels, is expected to be more effective than these low-permeability core examples in lowering the phreatic surface within the embankment and promoting stability. The Constancia and Highland Valley H-H dams are lower (the Yankee Doodle dam is higher) than the planned bulk TSF main embankment. These dams are still being raised.

The Applicant has provided eight other examples of dams that reportedly have similarities to the planned bulk TSF main embankment. Three of these dams are described as “Modified Centerline” dams, or hybrids of centerline and upstream or downstream construction with rockfill raises. These dams are somewhat comparable to the planned bulk TSF main embankment configuration. The other five dams are described as being raised using cyclone sand instead of rock fill, which means that the dams are not comparable to the planned bulk TSF embankment. Also see Section 4.15, Geohazards and Seismic Conditions, for more discussion of flow-through dam design.

At the current conceptual level of bulk TSF design, there is uncertainty regarding the ability of the tailings to drain sufficiently. It is uncertain whether the thickened tailings at 55 percent solids would segregate enough, with coarse tailings forming the tailings beach near the spigots, and finer tailings in the middle of the impoundment, to promote reduction of the phreatic surface near the main embankment (AECOM 2019n). Although the design is intended to promote unsaturated conditions, most of the tailings may remain saturated throughout operations, and potentially into post-closure. See Figure K4.15-3 for a cross section of the estimated phreatic surface.

Future tailings geotechnical investigations by field explorations, field and laboratory testing, and seepage, stability, and liquefaction analyses have been committed to by the Applicant in RFI 008h, and are described in Chapter 5, Mitigation. Additional analysis would further the understanding of tailings deposition behavior and help address this concern. See Section 4.15 and Appendix K4.15, Geohazards and Seismic Conditions, for additional details.

Success of the bulk TSF design would depend on the continued maintenance of low phreatic surfaces in the TSF, especially near the main embankment. Appropriate mitigation and monitoring plans would be critical to ensure compliance with the design. Requirements on details such as phreatic surface elevations in the TSF would be developed as part of the Operations, Maintenance, and Surveillance (OMS) manual.

After active mine operations cease, the bulk TSF would be closed by grading its surface so that all drainage would be directed off the TSF. This is known as dry closure. The tailings surface would be covered with soil and/or rock, and possibly a geomembrane liner that would act as a water barrier. This would prevent water from ponding on the TSF surface. The liner would reduce water infiltration into the tailings, thereby continuing to promote unsaturated conditions in closure.

K4.27.2.6 Very High Capacity Water Storage in Main WMP

The Applicant has designed the mine site layout specifically to allow for very high capacity water storage, with the goal of maintaining minimal fluid on the tailings surface. Any excess fluid that may begin to collect in the supernatant pond would be pumped to the main WMP, which is the key component of the TSF water management plan.

The very high capacity of the main WMP is one element that makes the mine layout unique with respect to other mine layouts. The main WMP is designed to manage surplus contact water from the mine site under the full range of climate conditions, including prolonged wet and dry periods. The average volume of planned contact water stored in the main WMP is approximately 1,470 million cubic feet (ft^3), with maximum storage of approximately 2,440 million ft^3. Storage capacity of the main WMP would also include storage of the required inflow design flood (IDF) (equal to the Probable Maximum Flood), and additional freeboard for safety (Knight Piésold 2018q). The very high capacity allows for storage of excess contact water from the bulk TSF in the main WMP, to maintain a minimal supernatant pond in the bulk TSF.

If the bulk TSF seepage control system cannot keep up with the surface water draining through the TSF, the phreatic surface could start to rise in the tailings. In this case, the excess surface water in the supernatant pond could be pumped to the main WMP. Likewise, if there were extreme precipitation events, to the extent that the water level began to rise in the TSF and the supernatant pond started to increase in size, that excess fluid could be pumped to the main WMP, and there would be adequate warning and time to do this safely without any risk to the stability of the main embankment.

Additionally, the bulk TSF itself has extra supernatant pond freeboard built into the design to temporarily hold the IDF, etc., if needed (see Section 4.15, Geohazards and Seismic Conditions).

K4.27.2.7 Dry Closure and Post-Closure

The bulk TSF closure plan would include a dry surface cover with precipitation drained off so that the TSF would ultimately become a dry landform. This is in contrast to mines with permanent water covers over the TSFs through to post-closure that would require long-term treatment of excess surface water and seepage, and would require continued stability assessments of the embankments as long as they are retaining water on the TSF surface.

The stability benefits of a dry closure are summarized by Cobb (2019b) as follows: “At the end of the operating life the risk is immediately reduced if the operational pond can be removed, resulting in a “dry” closure. After that, the risk is dependent on the nature of the design and the post-closure maintenance requirements.” The bulk TSF post-closure maintenance requirements would be developed as part of the closure design and post-closure objectives.

K4.27.2.8 Failure Modes and Effects Analysis Risk Assessment

In October of 2018, the US Army Corps of Engineers (USACE) hosted an EIS-Phase Failure Modes and Effects Analysis (FMEA) workshop to assess the likelihood of failures and the severity of potential environmental impacts from the major embankments in the bulk TSF, pyritic TSF, and main WMP, and to determine appropriate release scenarios for impacts analysis in the EIS. The FMEA workshop was preceded by the development of a draft list of potential failure modes that was updated as an initial part of the workshop.

Participants at the FMEA workshop used the available information on the Applicant’s design to assess the likelihood of various dam failure scenarios (potential failure modes), including a full tailings dam breach. The FMEA participants considered the design (as described above) and determined that the probability of a large-scale release of tailings was extremely low. See

Section 4.27, Spill Risk, and the EIS-Phase FMEA Report (AECOM 2018l) for full details on the FMEA risk assessment process.

K4.27.3 Examples of Four Recent Dam Failures

Numerous comments were received on recent tailings dam failures in British Columbia (Mount Polley in 2014) and Brazil (Fundão in 2015; Feijão in 2019). Note that the names Fundão and Feijão are used in this Technical Memorandum versus the media-used names of Samarco and Brumadinho, respectively, for two reasons: consistency with the independent review panel names in the failure review reports; and Fundão and Feijão are the mine names (like Mount Polley is a mine name) versus Samarco, which is the mine owner company name; and Brumadinho, which is the name of the nearest town to the mine.

Commenters expressed concern that similar failures could occur at the Pebble mine. These three tailings failures are reviewed here, along with a recent tailings dam failure in Australia (Cadia in 2018), for purposes of addressing the largest global tailings dam failures in the last 6 years. This section reviews these four recent tailings dam failures in the context of the similarities and differences between these facilities and the bulk TSF.

K4.27.3.1 Mount Polley Failure, British Columbia, Canada 2014

The Mount Polley mine near Quesnel Lake, British Columbia, Canada, had a failure of their TSF Perimeter Dam on August 4, 2014. A variety of factors led up to the dam failure, as outlined in the Chief Inspector of Mines report (BCMOE 2015) and the IEEIRP report (Morgenstern et al. 2015). Morgenstern (2018) provides recommendations for future TSF designs partly based on information from the Mount Polley TSF failure.

There was a change in dam design and construction to a steeper outer slope than engineers had originally designed; there was a deep clay layer beneath the foundation whose extent was underestimated and whose weakness was not sufficiently considered in the design; there was a history of water management that resulted in an occasional full water cover over the TSF; and there was a lack of regulatory oversight and enforcement to correct these inadequacies (Morgenstern et al. 2015).

At the time of the release, approximately 10 million cubic meters (m^3) of surface water were covering the TSF that should not have been present, per the water management plan. When the dam failed, this additional water eroded and entrained significant amounts of tailings. The total volume of the release was 17 million m^3 of water (surface water + interstitial water held within the tailings) plus 8 million m^3 of tailings solids (Morgenstern et al. 2015). The flood of fluid and tailings flowed down Hazeltine Creek and into Quesnel Lake.

The total release has been estimated to account for approximately 30 to 36 percent of the total volume of the TSF. This release estimate is based on information provided in the Chief Inspector of Mines report (BCMOE 2015) and other public data sources. Had the excess surface water not been present in the TSF, fewer tailings would have been entrained in the release, and the amount of released tailings and fluid would have been much lower.

The mine is in a remote area with no communities directly downstream of the dam. There were no human fatalities from the failure and ensuing flood.

The overall environmental impact was considered limited. Portions of Hazeltine Creek were damaged from erosion. Water quality downstream of the Mount Polley release was reduced for approximately 6 months, after which time the water quality returned to baseline (Nikl et al. 2016). Spilled tailings were recovered as was practicable from Hazeltine Creek, and the damaged channel was reconstructed. Salmon in the Quesnel Lake watershed downstream of the Mount

Polley release returned to spawn in high numbers in 2018, 4 years after the spill (Williams Lake Tribune 2018).

The failed Mount Polley Perimeter Dam had been constructed and raised by the centerline method. Tailings were deposited into the TSF as a conventional slurry. Excess water on the surface of the tailings eroded, entrained, and mobilized a significant amount of tailings, thereby increasing the volume of released tailings.

Comparison of the Mount Polley Perimeter Dam with the proposed bulk TSF main embankment on the Pebble Project is only in the method of dam construction; namely, the centerline method. This was not cited by either Morgenstern (2015) or the British Columbia Ministry of the Environment (BCMOE) (2015) as a contributary factor to the Mount Polley failure. Otherwise, the bulk TSF main embankment is planned to differ from the Mount Polley Dam in three main ways: 1) the bulk TSF embankment would be founded on bedrock without risk of overlying a weak soil layer; 2) tailings discharge into the bulk TSF would be with thickened tailings, not slurried tailings, thereby reducing the water volume in the bulk TSF; and 3) the supernatant pond on the bulk TSF surface would be kept small by pumping to the main WMP.

The first of these three differences is the application of fundamental soil mechanics and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The second and third factors are direct applications of the IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF, which are part of the proposed bulk TSF operations plan.

K4.27.3.2 Fundão Failure, Minas Gerais, Brazil 2015

The Fundão dam at the Germano iron ore mine near Bento Rodrigues, Minas Gerais, Brazil, experienced a failure on November 5, 2015. The owner of the mine is Samarco Mariana Mining (joint venture of Vale and BHP Billiton). The failure is often referred to as the "Samarco" dam failure, but it is referred to here as the Fundão dam failure, consistent with the Fundão Tailings Dam Review Panel report (Morgenstern et al. 2016) terminology. Morgenstern (2018) provides recommendations for future TSF designs partly based on information from the Fundão failure.

Tailings became liquefied and flowed out of the dam, with a total release of up to 60 million m^3. The flood of fluid and tailings flowed into the towns of Bento Rodrigues and Paracatu de Baixo, causing 19 fatalities and displacing hundreds more. The plume of tailings traveled down the Doce River, entering the Atlantic Ocean approximately 400 miles away 2 weeks later.

Two types of tailings of different grain sizes had been delivered to the TSF as fluid slurries. Much of the tailings were loose and fluid-saturated, and therefore susceptible to liquefaction. The approximately 100-meter (328-foot)-high dam was constructed and raised by upstream methods on top of previously deposited weak and saturated tailings, several hundred feet upgradient of the original tailings starter dam (Morgenstern et al. 2016).

The Fundão TSF had a multi-year history of design, construction, and operations changes that triggered liquefaction of the deeper tailings. These included: "(1) damage to the original Starter Dam that resulted in increased saturation; (2) deposition of slimes [finer grained tailings] in areas where this was not intended [which reduced drainage]; and (3) structural problems with a concrete conduit that caused the dam to be raised over the slimes" (Morgenstern et al. 2016). Ongoing drainage problems continued in the years prior to failure. A series of three small earthquakes occurred about 90 minutes prior to the dam failure, and "this additional movement is likely to have accelerated the failure process that was already well advanced" (Morgenstern et al. 2016). This failure could not be compared to potential failures at a properly designed, constructed, operated, and regulated facility.

There is no relevant comparison between the Fundão dam and the proposed bulk TSF main embankment on the Pebble Project. The bulk TSF main embankment is planned to differ from the Fundão dam in five main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened rather than slurried tailings, thereby reducing the water volume in the bulk TSF; 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains; and 5) the supernatant pond on the bulk TSF surface would be maintained at a small volume by continually pumping the surface water to the main WMP.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The remaining differences are direct applications of the Mount Polley IEEIRP advocacy for reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.3.3 Feijão Failure, Minas Gerais, Brazil 2019

On January 25, 2019, there was a failure of dam B-1 at the Córreigo de Feijão iron ore mine near the town of Brumadinho, in the state of Minas Gerais, Brazil. Official information on this failure was not available during the DEIS preparations and the comment period. Official information on the failure only became available in December 2019, with the release of the Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam (Robertson et al. 2019):

> This dam failure is unique in that there are high quality video images of the event that provide insight into the failure mechanism. …The videos clearly show a slope failure within the dam starting from the crest and extending to an area just above the First Raising (the Starter Dam). The dam crest dropped and the area above the toe region bulged outwards before the surface of the dam broke apart. The failure extended across much of the face of the dam and collapse of the slope was complete in less than 10 seconds, with 9.7 million cubic meters (Mm^3) of material (representing approximately 75 percent (%) of the stored tailings) flowing out of the dam in less than 5 minutes (min).

It is noted that slope failure of the B-1 dam released 9.7 million m^3 of wet tailings, which calculates to 75 percent of the total tailings that were stored in the TSF. This ratio of tailings release is almost double and quadruple the flow ratios that were derived from historic data, and used in the two flow models described below. The failure resulted in a catastrophic mudflow that traveled rapidly downstream, resulting in 270 fatalities. A 75-mile length of the Paraopeba River was contaminated. Toxic levels of lead and chromium were measured in the first 12 downstream miles.

The B-1 dam that failed was constructed using the upstream method, in which dam raises are constructed on top of weak underlying tailings, and had a relatively steep upstream slope. Tailings had been deposited in the TSF as slurry. No tailings had been deposited in the facility since 2016, but the phreatic surface did not drop significantly after tailings deposition ended.

Tailings were dominantly non-PAG, like those of the Applicant's bulk tailings, and did not require subaqueous cover. Therefore, there was no full water cover over the tailings, but the phreatic surface was quite high, so that most tailings were fluid-saturated.

The dam was monitored and reportedly showed no signs of deformation or change prior to failure (Robertson et al. 2019). Installed drainage provisions were insufficient, and drainage was impeded, particularly through the toe of the dam, resulting in a high phreatic surface. Seepage from the dam was observed periodically. The dam failed in the middle of the wet season, so precipitation also contributed to the high phreatic surface.

The tailings were not able to drain properly, and were predominantly loose and saturated, and therefore highly susceptible to liquefaction and flow. The Report of the Expert Panel states that "[W]ater management within the tailings impoundment…at times allowed ponded water to get close to the crest of the dam, resulting in the deposition of weak tailings near the crest"; and that the tailings were heavy and brittle due to their high iron content, to the extent that "significant parts of the dam were under very high loading due to the steepness of the dam, the heavy weight of the tailings, and the high internal water level" (Robertson et al. 2019). The failure "was the result of flow (static) liquefaction within the materials of the dam" (Robertson et al. 2019).

There is no relevant comparison between the Feijão dam and the proposed bulk TSF main embankment of the Pebble Project. The bulk TSF main embankment is planned to differ from the Feijão dam in five main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened and not slurry tailings, thereby reducing the water volume in the bulk TSF; 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains; and 5) the supernatant pond on the bulk TSF surface would be maintained at a small volume by continually pumping the surface water to the main WMP.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The remaining differences are direct applications of the Mount Polley IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.3.4 Cadia Failure, New South Wales, Australia 2018

The first three failures reviewed above were cited in comments on the DEIS, because they were large-scale releases involving significant impacts, including loss of life and environmental impacts. Here a recent failure from another TSF is addressed, which is somewhat distinct from the preceding three facilities. Note that official information on this failure was not available during the DEIS preparations. Official information on the failure became available in April 2019 with the release of the Independent Technical Review Board (ITRB) report (Jefferies et al. 2019).

The Newcrest Cadia copper mine near Orange, New South Wales, Australia, stores tailings in two TSFs behind dams that were raised by upstream construction methods, with the upper dam that contains the Northern TSF (NTSF) directly upgradient of the lower dam that contains a lower TSF. Tailings are dominantly non-PAG, similar to the Applicant's bulk tailings, and do not require subaqueous cover. Therefore, the tailings facilities are not water-inundated. Tailings are delivered as a slurry. The TSF at Cadia is more analogous to the Applicant's bulk TSF in that the tailings are not under a water cover, and there is just a small supernatant pond.

On March 9, 2018, there was an embankment failure at the NTSF. The ITRB report described that in the failure, the downstream slope of the NTSF slumped, so that tailings containment was lost (Jefferies et al. 2019). The failure resulted in a relatively viscous flow of tailings, because there was no ponded surface water involved, but tailings were saturated. Very few tailings were mobilized, because there was no excess fluid to entrain them. The small amount of tailings released from the TSF was captured in the lower TSF. There was no release of tailings or fluid outside of mine facilities; therefore, there were no resulting environmental impacts. The worksite was evacuated prior to the failure, and there were no injuries or loss of life (Jefferies et al. 2019).

The failed NTSF dam was constructed initially by downstream methods and was later raised by upstream methods. Tailings were delivered as a conventional slurry. The stored tailings were saturated and loose, so that they were susceptible to liquefaction if triggered (Jefferies et al. 2019).

The failure was concluded to have resulted from foundation instability, likely due to a weak, low-density volcanic unit in the vicinity of the slump. “Other factors contributing are the local height of the dam, the prevailing phreatic conditions, and the additional excavation at the toe of the structure” (Jefferies et al. 2019). The resulting deformation of the dam consisted of slow initial movement for many months prior to failure “as the failing mass adjusted to changing states of equilibrium” followed by “relatively sudden losses of resistance and/or increases in loading to create conditions to accelerate movements to the distances ultimately achieved” (Jefferies et al. 2019). Two small seismic events in the days preceding (4.3 magnitude) do not appear to have contributed to the liquefaction (Jefferies et al. 2019).

Construction work was under way before, and up to the time of failure, for purposes of improving the already marginal stability of the NTSF dam. This construction increased the potential for the outward movement of the embankment, and was a contributory factor in triggering movement of the dam that led to the mobilization of the tailings by static liquefaction.

The only relevant comparison between the Cadia dam and the proposed bulk TSF main embankment on the Pebble Project is the Cadia effort to maintain a minimal surface water pond. The bulk TSF main embankment is planned to be different from the Cadia dam in four main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened, rather than slurry tailings, thereby reducing the water volume in the bulk TSF; and 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The last two differences are direct applications of the Mount Polley IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.4 Tailings Dam Failure Modeling

Although the probability of a catastrophic tailings failure of the bulk TSF main embankment is very remote (see Section 4.27, Spill Risk), there is public concern regarding the installation of any new TSFs, especially when there are human populations and/or fragile ecosystems downstream of the facilities.

Scientists and engineers have sought to learn more about these potential dangers and how to avoid them through modeling correlated with previous failure study findings. Tailings dam failure modeling can demonstrate potential impacts to downstream environments with reasonable accuracy if the modeling is performed using site-specific information versus hypothetical or assumed information. Modeling efforts vary greatly in their quality and usefulness.

For example, models can be very useful in predicting the potential outcomes of tailings releases when they include site-specific information such as TSF site and downstream topography; geologic, seismic, geotechnical, and hydrologic data; tailings rheology (branch of physics that deals with flow of solid and liquid materials), moisture content, and density; and TSF design, construction, and operations and management plans. On the other hand, models that do not include these specifics and assume values for them cannot predict to reasonable accuracy the failure outcomes such as volume of release, downstream impacts, and extent of inundation.

Two models were developed in the last 6 years in efforts to model a catastrophic tailings dam failure of a hypothetical TSF at the proposed Pebble mine. These models were developed by the EPA (2014) and Lynker Technologies, LLC (Lynker 2019).

The models are not relevant to the bulk TSF main embankment because the model assumptions are based on historic failures from water-inundated TSFs, most of which stored conventional tailings slurries and not thickened tailings. The models therefore assumed a high volume of water involved in the release, which erodes, entrains, and/or mobilizes tailings, leading to a larger release of both fluid and solid tailings. However, the Applicant’s design would have only a small supernatant pond, and not a full water cover. Without a full water cover, bulk TSF tailings would not be triggered to experience static liquefaction and flow.

Therefore, the modeled releases and resulting impacts are an overestimation of a reasonable bulk TSF failure scenario.

Below is a review of the EPA and Lynker models, indicating where they are and are not relevant for an environmental review of the project.

K4.27.4.1 EPA Model

The EPA (2014) model/series of models was put forth in 2014 as part of the EPA Bristol Bay Watershed Assessment (EPA 2014), which was an assessment of potential mining impacts on salmon ecosystems of Bristol Bay. This model was rather general, because it was based on a hypothetical mine with several assumptions made, and the modeling used an earlier, but now obsolete, mining plan (Wardrop 2011) that was developed several years prior to the Applicant outlining its current mining plan.

It is noted that the EPA model was developed before the Mount Polley, Fundão, Cadia, and Feijão failures occurred, and therefore EPA did not have the results and lessons learned from these failures to use as case histories for its modeling.

The EPA evaluated three hypothetical Pebble mine scenarios (Pebble 0.25, Pebble 2.0 and Pebble 6.5). Each scenario represents a different mine size based on different stages of potential mining of the total deposit. These scenarios were based on processing 0.25, 2.0, and 6.5 billion tons of ore in 20, 25, and 78 years, respectively. For comparison purposes, the current Pebble Project is based on mining 1.44 billion tons of ore over 20 years, so its size fits between the Pebble 0.25 and 2.0 scenarios.

EPA describes the scenarios as follows:

> The three mine size scenarios evaluated in the assessment represent realistic, plausible descriptions of potential mine development phases, consistent with current engineering practice and precedent. The scenarios are not mine plans: they are not based on a specific mine permit application and are not intended to be the detailed plans by which the components of a mine would be designed. However, the scenarios are based on preliminary mine details put forth in Northern Dynasty Minerals’ Preliminary Assessment of the Pebble Mine (Wardrop 2011), as well as information from scientific and industry literature for mines around the world …. Thus, the mine scenarios reflect the general activities and processes typically associated with the kind of large-scale porphyry copper mine development likely to be proposed once a specific mine application is developed.

Each EPA scenario had its largest tailings dam sited on approximately the same footprint as the currently proposed bulk TSF main embankment. At the time, the available Pebble reports had suggested that this dam could be up to 209 meters (686 feet) high. The EPA evaluated two potential failures of this dam: one with the dam 92 meters (302 feet) high, which corresponds to the full height of the Pebble 0.25 scenario; the other with the dam at its full height of 685 feet for both the Pebble 2.0 and Pebble 6.5 scenarios. The modeling assumed that bulk and pyritic tailings would be combined into one or more TSFs, which was the proposed plan at the time, rather than a separate bulk TSF and pyritic TSF, as is the current plan.

In a summary table of the scenario assessments, EPA outlines these assumptions:

> All water collection and treatment at site works properly, and wastewater is treated to meet state and national standards before release; however, some leachate from waste rock and TSFs is not captured. …Excess water stored in TSF 1 is released over the spillway. …Stormwater falling onto TSFs would be stored in the tailings impoundments and used in the process water cycle. …Prior to active mining, but after the starter dam was built for TSF 1, site water would be diverted to TSF 1 to allow sufficient water for process plant startup. During mine operation, groundwater and precipitation would be pumped from the mine pit to prevent flooding of the mine workings. …Water would be needed for the flotation mill, to operate the TSF, and to maintain concentrated slurry in the product pipeline. …For example, much of the water used to pump the tailings slurry from the mill to a TSF becomes available when the tailings solids settle, and excess overlying water is pumped back to the mill. …[At closure] the tailings pond would be drawn down to prevent flooding and to maintain stability, but a pond of sufficient depth would be retained to keep the PAG tailings hydrated and minimize oxidation.

These assumptions show that the model input included slurried tailings, not thickened tailings discharge, and an assumed bulk TSF operation with a full water cover versus a planned small pond by pumping surface water to the main WMP. The assumption of a large water cover in the bulk TSF skewed the model results because a larger water volume would mobilize more tailings in the event of a dam breach, and therefore cause a larger tailing release than could occur. A larger volume of tailings would be released as a result of a dam breach if the TSF contained slurry tailings and a large surface pond, as was planned at the time of the modeling, than if the TSF contained thickened tailings and a small pond.

Following a discussion on tailings dam failure probabilities based on historic failure reviews, the EPA correctly stated:

> The historical frequencies of tailings dam failures presented above may be interpreted as an upper bound on the failure probability of a modern tailings dam.…improvements in the understanding of dam behavior, dam design, construction techniques, construction quality control, dam monitoring, and dam safety assessment would be expected to reduce the probability of failure for dams designed, constructed, and operating using more modern or advanced engineering techniques.

Similarly, dam breach and tailings release model analysis methods have advanced in recent years (McPhail 2015; Martin et. al. 2019) as described below.

In its modeling, the EPA used a combined bulk and pyritic tailings bulk density of 53 percent solids and 47 percent water by volume. This equates to a water content of approximately 33 percent water by weight. This water content is within the 20 to 35 percent range for deposited tailings that were discharged as a slurry, but high for deposited tailings that are discharged as thickened tailings.

EPA (2014) used the USACE Hydrologic Engineering Center's River Analysis System (HECRAS) to model the hydrologic characteristics of the dam failures. This tool requires the selection of one of two failure initiation mechanisms: overtopping the dam; or piping (internal erosion) in the embankment. Overtopping was selected, but piping was used for sensitivity analyses. Results were similar. The study first modeled the hydrologic conditions (e.g., water discharges, depths, and velocities) in the stream channel and floodplain during and immediately following dam failure, and then used this output to estimate tailings transport and deposition along the stream network. EPA acknowledged the limitations of the model for tailings flows with high levels of sediment, because the model was developed for fluid flows with lower viscosity.

This modeling is not relevant to a failure of the bulk TSF because the model assumes that a high volume of water is stored in the TSF, making overtopping the dam more probable, and resulting in an increased volume release (both tailings and fluid). Based on the current design, overtopping is a remote possibility, because the operations plan calls for only a small surface pond, and not a full water cover (because excess water would be pumped to the main WMP). In addition, the model was developed to predict low-viscosity fluid flows versus higher-viscosity tailing flows.

The EPA analysis assumed that 20 percent of the tailings in the TSF would be released in the event of a dam failure. EPA considered this to be a conservative estimate in the range of historic tailings dam failures. EPA added that the ratio of tailings that would be released in the event of a dam failure could exceed 20 percent. No justifications are given on the 20 percent assumption, except that it is in the range of historic tailings dam failures, and on the comment that the release could be larger than 20 percent. There is also no discussion on the possibility that the release could be less than 20 percent, which is discussed below.

The EPA acknowledged that the range of estimated dam failure probabilities is wide, reflecting the great uncertainty concerning such failures, and then described that the most straightforward method of estimating the annual probability of a tailings dam failure is to use the historical failure rate of similar dams. Three reviews of tailings dam failures produced an average rate of approximately 1 failure per 2,000 dam-years, or 5×10^{-4} failures per dam-year, and that expected failure could occur any year in that 2,000-year window, with an average annual probability of 0.0005, or 5×10^{-4}.

The EPA then correctly argued that the record of past failures does not fully reflect current engineering, design, construction, operating, and monitoring practices, as would be used on the bulk TSF. EPA stated that some studies suggest that improved practices can reduce the failure rate by an order of magnitude or more, resulting in an estimated failure probability of failure of 1 in 250,000 per year for facilities designed, built, and operated with state-of-the-practice engineering (Category I facilities); and 1 in 2,500 per year for facilities designed, built, and operated using standard engineering practice (Category II facilities). The advantage of this approach is that it addresses current regulatory guidelines and engineering practices. The disadvantage is that it is not known if standard practice or state-of-the-practice dams would perform as expected, particularly with dam heights and subarctic conditions in these scenarios.

EPA limited the extent of the model to a 30-kilometer (19-mile) reach downgradient of the bulk TSF down the North Fork Koktuli River (NFK) valley to the confluence of the South and North Fork Koktuli rivers. It was considered that extending the simulation beyond this point would introduce error and uncertainty associated with the contribution of South Fork Koktuli River (SFK) flows. The results showed that the dam failure in all three mine scenarios would result in a flow of tailings into the NFK that would scour the valley and deposit many meters of tailings in a sediment wedge across the entire valley near the dam, with lesser quantities of tailings deposited as far as the NFK's confluence with the SFK. The tailings flow would continue down the mainstem Koktuli

River with similar effects, the extent of which was not estimated because of the model and data limitations.

K4.27.4.2 Lynker Model

The Lynker (2019) model was developed for the Nature Conservancy and Bristol Bay Regional Seafood Development Association prior to the release of the DEIS. The model used the publicly available information on the mine site and design, but did not address the planned use of BAT (Morgenstern et al. 2015) to minimize the water volume in the bulk TSF by discharging thickened versus slurried tailings, and to maintain a small supernatant pond by pumping to the main WMP versus allowing a large supernatant pond to develop.

It is noted that the Lynker model was developed after the Mount Polley and Fundão failures occurred, therefore, Lynker had access to the investigation findings of these failures as case histories. However, although the Lynker modeling was also completed after the Cadia and Feijão failures, it was prior to the release of the investigation reports of these failures; therefore, the Cadia and Feijão investigation reports were not available.

Lynker completed a model analysis of flow and deposition for a failure of the bulk TSF main embankment at approximately the same location as the Applicant’s embankment. The analysis used the publicly available data from the Pebble Project. Lynker cited the following four aspects of the project to suggest that a full tailings breach was not “extremely unlikely”: centerline versus downstream construction; TSF size ten times larger than TSFs of recent failures; 52 inches of annual rainfall; and seismic risks that could lead to dam failure by liquefaction.

These aspects are all controllable by application of BATs. Centerline dams are a sound technical and economic compromise between downstream and upstream dams, and can be designed to be as stable as downstream dams, especially on thickened tailings. The static Factor of Safety (FoS) for both the downstream and centerline dam alternatives would be 1.9 to 2.0 (see Section 4.15, Geohazards and Seismic Conditions).

Tailings characterization to the maximum extent possible is critical to the design of a safe TSF and assessment of tailings flow characteristics in the event of an embankment failure. However, a calculated FoS can be misleading with respect to reduction in risk because the FoS depends on the level of engineering used to develop it. Silva et al. (2008) and Altarejos-Garcia (2015) show that the level of engineering, or level of detail in the engineering, has a greater influence on the probability of failure than increasing the FoS. This is echoed by the Australia National Committee on Large Dams (ANCOLD 2012, updated 2019) guidelines as follows: “There are no “rules” for acceptable factors of safety, as they need to account for the consequences of failure and the uncertainty in material properties and subsurface conditions.” Similar conclusions are outlined in the Alaska Department of Natural Resources Draft Guidelines for Cooperation with the Alaska Dam Safety Program (ADNR 2017a), and summarized by Cobb (2018, 2019b).

FoS values described for the bulk TSF main embankment are based on the current conceptual levels of design. FoS values would be refined during the advanced preliminary and detailed stages of the designs.

The dam size can be controlled, as shown by other operating tailings dams of similar heights. Rainfall can be accommodated as shown by tailings dams in similar rainfall environments in Alaska and worldwide, such as the Gibraltar and Brenda mines in British Columbia and the Continental Mine in Montana, which have centerline or modified centerline TSFs in the range of 385 to 750 feet in height. Seismic design criteria are an established science that can be used to accommodate the required design earthquake on a large dam.

Lynker developed its model using a FLO-2D software package that is a flood modeling package capable of simulating non-Newtonian flows (i.e., high-viscosity, sediment-laden flows) that characterize tailing failures. Sensitivity analyses were performed by changing parameters, including tailings release volumes and durations. The model expanded on the EPA analysis in two ways: by extending the model domain about 140 kilometers (88 miles) down the Koktuli river system to just below the confluence of the Mulchatna and Nushagak rivers, while the EPA model domain only extended 30 kilometers (19 miles) downstream; and by simulating the bulk TSF failures as a non-Newtonian flow consistent with tailings flow that would have sediment concentration with different rheology than a clear flood flow.

The release scenarios in the Lynker study are based on data from historic TSF failures compiled by Rico et al. (2007a, b) and Laurrali and Lall (2018) that date back to the 1970s. These early TSFs were mostly storing wet tailings slurries, predominantly built by upstream construction methods, and mostly under a relatively full surface water cover in traditional large “lagoon” type TSFs. Therefore, they are not applicable to the Pebble design with thickened tailings that would not be covered by water. Most historic failures were also from upstream dams, which are less stable than centerline or downstream dams. In addition, most of the failures involved dams founded on soil or tailings, instead of a bedrock foundation that is planned for the bulk TSF main embankment.

For its model, Lynker’s starting point was a calculation that 41.7 percent of the tailings would be released. This was based on an empirical formula developed by Rico (2007b) from pre-2007 failure case history studies, and is twice the 20 percent tailings release rate that EPA (2014) used in its analysis. Rico’s data are mostly based on slurry tailings retained by upstream tailings dams, versus thickened tailings retained by a centerline dam. Dam break tailings releases of 10 and 60 percent were also tested to determine their impacts to the Nushagak watershed.

The 41.7 percent tailings release volume is also excessive when compared to data discussed below, and the fact that a significantly smaller release would be expected of thickened tailings in a TSF with a small pond that would likely not have enough entrained and surface water to mobilize and sustain a large tailings flow. As described below, there are methods for calculating the breach size and release volume based on site conditions, tailings properties, and TSF operations; versus using a formula based on slurried tailings and upstream raise failure histories.

The Lynker model relied on the 11- and 24-hour breaches as most likely scenarios, and the results primarily illustrate the 24-hour breach, because it is a more conservative estimate with a lower peak flow compared with the 11-hour breach. The 11-hour breach was found to be more impactful. The Lynker modeling analysis does not seem to have addressed modes of dam failure or failure initiation mechanisms like the EPA analysis did when it selected overtopping, and also used piping for sensitivity analyses. The Lynker analysis simply selected a 41.7 percent tailings flow based on inappropriate historical data, and then performed the modeling.

The Lynker model indicated that tailings from a bulk TSF main embankment breach would travel more than 75 kilometers (47 miles) downgradient, beyond the confluence of the Mulchatna River, where most of the model simulations ended. In an expanded model domain, the results indicate that tailings under most scenarios would continue beyond the Nushagak River, more than 130 kilometers (81 miles) downgradient. The modeling showed that 50 percent of the tailings were still moving through the downstream boundary of the expanded model, and are “extremely likely” to continue to Bristol Bay. (Note that in both of the EIS tailings release models, a small amount of suspended tailings particles were modeled to extend the full length of the downstream watershed, through the Nushagak River to Bristol Bay.)

K4.27.4.3 Model Discussion

The EPA and Lynker models were developed by competent teams of scientists, and the model methods are scientifically valid and worthy of review. However, the problem with both models when used for NEPA analysis is that they do not account for the Pebble mine specifics put forth by the Applicant (as reviewed above). Instead, they are based on generic historical data for past dam failures, most of which involved TSFs that differ from the proposed bulk TSF as described above. Some of the model deficiencies and the differences between their assumptions and the planned bulk TSF are described in the following paragraphs.

Both models started with an assumed volume of tailings release based on historic tailings dam failures (Rico 2007a) without regard for the differences between the Pebble bulk TSF and the historic TSFs that failed. This is the reverse of how modeling should be performed; namely, the tailings release should be estimated as part of the modeling based on site-specific data outlined above. Then an appropriate volume of release would be determined as part of the modeling process. Larrauri and Lall (2018) outline the need to consider the potential energy associated with the released volume as opposed to the whole TSF volume.

Lynker noted that depending on the size of the TSF, Rico’s formula shows that the expected tailings slurry release from a TSF failure is 35 to 45 percent of the total TSF volume. Later, Azam and Li (2010) concluded that on dam breakage, the released tailings generally amount to 20 percent of those contained in the facilities. Rico (2007b) stated the following: “The application of the described regression equation for prediction purposes needs to be treated with caution and with support of on-site measurements and observations.” These cautions are supported by later case history studies by Martin et al. (2019) that show that tailings slurry released from a TSF failure could range from 1 to 100 percent of the total TSF volume.

As described above, the result of a release of thickened tailings in the event of a failure, “would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 20 times the dam height), unless the material slumps into a water body” (MEND 2017). This would predict that a full failure of the bulk TSF main embankment would result in a tailings release extending for a distance of approximately 2.2 miles from the bulk TSF main embankment.

Therefore, the use of a precise 41.7 percent as the basis for a tailings breach model analysis is inconsistent with a wide range of historic data, and the use of historic data from slurry tailings releases is misleading when applied to thickened tailings releases.

Marr (2019) reviewed the failure histories of ten TSFs, including the four failures described above. From his reviews, he developed the following characteristics of tailings dam failures:

> Failure can occur quite suddenly will little to no warning; Generally, something triggers a failure within the barrier dam or foundation which results in loss of containment of tailings; This triggers the stored tailings to liquefy; Liquefied tailings can flow very fast for long distances and present great risk to downstream people and environment; Little time to warn and evacuate people within a few km below the dam; Visual inspections may not reveal the threat of imminent failure; Most monitoring systems will not give adequate warning; These characteristics should be strongly considered in the design and operation of a tailings dam.

A key factor in Marr’s findings is that tailings do not just mobilize and flow without a trigger. The trigger is typically a failure of the dam or embankment that is retaining the tailings, which then allows water, in the tailings and on the tailings surface, to mobilize and cause the tailings to liquefy and flow out of the TSF. Again, excess supernatant fluid contributed to the tailings dam failure at Mount Polley (BCMOE 2015). The bulk TSF BAT plan of water removal from the bulk TSF by means of discharging thickened tailings versus slurry tailings and minimizing the surface pond by pumping water to the main WMP would significantly reduce the risk of a large tailings flow release as a result of an embankment breach.

A more appropriate project-specific method for conducting a tailings dam breach analysis using site data and operation plans could be the McPhail (2015) approach. This is a semi-quantitative risk assessment and a probabilistic analysis performed in the following sequence: fault (or cause) analysis; event tree analysis; and probabilistic flow slide. These sequences are described below.

The fault tree analysis enables a probability to be developed from the TSF management and performance to one of five flow-slide trigger faults that were identified by reviews of historic tailings failures: embankment static instability; embankment dynamic instability; embankment overtopping; embankment piping as a result of layers in the embankment fill; and delivery pipe or buried drainage failure. In developing the fault trees, a chain of sub-faults could precipitate a trigger cause that early management intervention could eliminate before the cause can trigger a failure. In assigning probabilities to the effectiveness of management intervention, the prevailing mining economic climate must be considered, because studies show a prevalence of failures during enforced austerity (McPhail 2015; Bowker and Chambers 2015; Armstrong et al. 2019).

It is interesting that the EPA (2014) analysis addressed the trigger faults, but the Lynker (2019) analysis was silent on the trigger faults. The concept of the trigger faults, as well as dam failure scenarios, are also discussed by Martin et al. (2019).

The event tree analysis then establishes the probabilities of loss of life, environmental damage, and loss of production if a flow slide results from a dam failure. Event trees start with the top fault and proceed by assigning probabilities associated with the following questions that define progressively developing events given a top fault: does a slide occur; are people present at the failure or in the flow path; would there be a plant stoppage and production loss; and mortalities?

The flow slide analysis is then performed by applying dam break analysis methods to tailings flow studies, and recognizing the difference between a tailings dam break analysis, and a water storage dam analysis, and therefore considering the effect of the following: tailings rheology; parabolic shaped tailings failure surface versus horizontal water flow surface; topographic ground slope along the slide flow path; and flow continuity. The flow continuity would be a critical factor for the bulk TSF because thickened tailings with a limited surface water pond cannot undergo a significant flow because of the lack of water to mobilize such flow.

McPhail (2015) developed a flow slide analysis method with input parameters: flow volume released; breach width; tailings rheology defined by tailings yield stress and viscosity properties; flow profile curvature; and tailings post-liquefaction friction angle that defines the residual angle of the resultant tailings crater in the TSF. Extensive testing is required to obtain these data. Therefore, a more practical approach is to use probabilistic calculations to establish confidence limits. Historic observations show that the tailings crater can be approximated by a truncated cone. Progressive development of the crater determines the flow slide outflow hydrograph, breach width, and tailings release volume.

Observations suggest three potential modes by which the flow slide can develop after liquefaction starts. The failure mode most likely for each situation depends on the liquefied tailings characteristics, with shear strength, rheology, and available water volume being key factors.

This approach estimates the tailings release upper and lower bounds by considering the TSF geometry and depth. Past failure evaluations indicate releases of 5 to 50 percent of the total TSF volume, breach widths of 250 to 1,000 feet, and crater slopes of 0.55 to 3.3 percent, plus ranges of tailings yield stress and viscosity. Therefore, a Pebble bulk TSF with thickened tailings and small water pond should be at the low end of the tailings volume release range, possibly much less than the EPA (2014) and Lynker (2019) volumes of 20 and 41.7 percent, respectively.