4.15 GEOHAZARDS

This section describes potential impacts of geologic hazards (geohazards) on project components that could affect the environment. The Environmental Impact Statement (EIS) analysis area for geohazard ranges from the immediate vicinity of the project footprint (e.g., slope instability) to regional areas with geohazards that could affect project facilities from long distances (e.g., earthquakes, volcanoes).

The impact analysis for geologic hazards considered the following factors:

- Magnitude – impacts are assessed based on the magnitude of the impact, as indicated by the anticipated effects of various possible geologic hazard events (e.g., repairable damage to mine features, ground settlement).
- Duration – impacts are assessed based on the project phase that they are expected to occur in (e.g., certain structures removed at closure), and how long repair of potential damage or interruption of activities may last.
- Geographic extent – impacts are assessed based on the location and distribution of occurrence of the expected effects from potential geologic hazard events (e.g., distant earthquake effects on mine site and port structures).
- Potential – impacts are assessed based on the likelihood of a geologic hazard event to occur during and after project development (e.g., based on expected recurrence interval[1] for certain geologic hazards).

The impact analysis incorporates an understanding of the probability of occurrence, and of planned mitigation in the form of planning, design, construction, operations, maintenance, and surveillance that can meaningfully reduce impacts from geohazards through closure and post-closure. Based on Pebble Limited Partnership (PLP) plan documents and engineering reports, planned mitigation methods (e.g., design and monitoring to withstand or detect geohazards) are considered part of the project description, and the impacts analysis includes this understanding. In some cases, planned mitigation may not be specified, but is considered typical or standard engineering practice. In cases where planned mitigation is unknown or unclear and the situation is not commonly addressed, the impact analysis takes the lack of planned mitigation into account.

This section describes the following potential impacts related to geohazards:

- stability of major mine structures during operations and closure.
- effects of earthquakes on project facilities.
- effects of unstable slopes on project facilities.
- effects of geotechnical conditions and coastal hazards on port structures and pipeline landfalls.
- effects of tsunamis and seiches on port and ferry terminals.
- effects of volcanoes on project facilities.

Potential impacts to the environment resulting from geohazard-caused upset conditions, such as an embankment failure, are addressed in Section 4.27, Spill Risk. As described in Section 3.14, Soils, permafrost has not been encountered in the mine site or other project areas based on field investigations; therefore, potential effects from permafrost hazards are not addressed in this section.

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[1] **Recurrence interval** (or return period) is an estimate of the probability or frequency that certain geohazards are expected to occur, based on geologic and seismologic evidence.

Scoping comments expressed concerns that major faults occur in the proposed project area and may affect project facilities. Commenters requested that the EIS include detailed information about seismically active areas, geological faults and tectonic activity, and corresponding design features. They also requested information on how the proposed project facilities, particularly the tailings storage facility (TSF), would withstand earthquakes, and an analysis of potential impacts from volcanic activity, especially at Amakdedori port and along the pipeline, from Augustine Volcano.

4.15.1 No Action Alternative

Under the No Action Alternative, the Pebble Project would not be undertaken. No construction, operations, or closure activities would occur. Therefore, effects on project components from geohazards, seismic events, and other geotechnical conditions would not occur as a result of this alternative, and no impacts on the environment would result from such effects. Permitted resource exploration activities currently associated with the project may continue (ADNR 2018-RFI 073). PLP would have the same options for exploration activities that currently exist. In addition, there are many valid mining claims in the area and these lands would remain open to mineral entry and exploration. Natural geohazards such as those described in Section 3.15, Geohazards, would continue to affect existing communities and infrastructure in the region.

4.15.2 Alternative 1 – Applicant's Proposed Alternative

4.15.2.1 Mine Site

This section describes potential effects of seismic events and other geohazards on major structures at the mine site; the ability of the structures to withstand these hazards; and the likelihood that such hazards could produce related environmental impacts. Figures in Chapter 2, Alternatives, display the mine site layout; and Table K4.15-1 in Appendix K4.15 provides the buildout dimensions of embankments and impoundments that would contain tailings, waste rock, and/or contact water at the mine site. This section also addresses potential geohazard effects on the open pit.

Embankment Construction Material

The embankments for the tailings and water management facilities would be constructed of drilled and blasted bedrock removed from quarries A through C[2], and the overburden in the open pit (Chapter 2, Alternatives, Figure 2-4). Analyses were completed to determine the quantities of on-site embankment construction materials and project-related needs. Appendix K4.15 (Table K4.15-2 and Table K4.15-3) provide embankment material quantities that would be generated by quarries A through C and the open pit overburden, as well as the embankment material needs for the relevant mine site-related facilities, respectively.

Based on review of material properties and quantities provided by PLP (2018-RFI 015b; PLP 2019-RFI 108a), the combination of the three quarries and the open pit overburden would generate sufficient materials (between 6 and 32 percent more rockfill material than needed) to construct the embankments. Thus, the likelihood that additional material needs would be identified as the project progresses (with related project footprint increases) is low.

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[2] Quarry A is shown as situated in the footprint of the bulk TSF; this quarry would be developed before the construction of the bulk TSF.

Embankment and Impoundment Design and Construction

The embankments and impoundments could be impacted by geohazards, including instability associated with seepage, internal erosion[3], and seismic (earthquake) events. The embankments would therefore be designed and constructed to be stable under both static (non-seismic) and seismic conditions, which is also required by relevant draft dam safety guidance documents (ADNR 2017a). The following summarizes the geohazard considerations for the proposed design and construction of the major embankments and impoundments, including the bulk TSF, pyritic TSF, water management ponds (WMPs), and seepage collection ponds (SCPs). More detailed information is provided in Appendix K4.15.

Bulk TSF. The bulk TSF would be designed to impound the bulk tailings, and includes a main (north) and south embankment with the following design and construction elements to prevent geohazard-related impacts:

- Siting in a single tributary watershed surrounded by bedrock knobs to focus potential impacts in one watershed and incorporate natural containment elements.
- Main (north) embankment centerline constructed[4] to reduce the footprint, with a buttressed downstream slope to enhance stability, which would result in 2.6 horizontal: 1 vertical (H:V) downstream embankment slope and a serrated near-vertical upstream face at the dam crest for the upper 280 feet of the embankment (Chapter 2, Alternatives, Figure 2-8).
- Permeable flow-through design with core/filter/transition zones materials to minimize water buildup in the TSF, prevent internal erosion, and remain functional after a seismic event.
- South embankment constructed using downstream methods[5], to include a downstream liner combined with a grout curtain to prevent upgradient groundwater flow into and beneath the impoundment.
- Bottom of south embankment core/filter/transition zones would tie into the top of the grout curtain zone, which would be keyed into bedrock to prevent leakage beneath the embankment.
- Underdrains beneath the TSF to further manage seepage flow.
- Water management to protect the dam from seepage pressure-related instability.
- Drainage ditches at the toe of the embankment slopes to prevent erosion and undercutting.
- Freeboard to contain the entire inflow design flood above the tailings beach.
- Excess pond water to be pumped to the main TSF SCP or main WMP.
- Higher south embankment elevation to direct overflow to water catchment facilities.

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[3] **Internal erosion**, also referred to as piping, is the formation of voids in a soil caused by the removal of material by seepage, and occurs when the hydraulic forces exerted by water seeping through the pores and cracks of the material in the embankment are sufficient to detach particles and transport them out of the embankment structure.

[4] **Centerline construction** is a method of dam (embankment) construction in which a rockfill dam is raised by concurrent placement of fill on top of the dam crest, the upstream slope including portions of the tailings beach, and the downstream slope of the previous raise.

[5] **Downstream construction** is a method of dam (embankment) construction in which a rockfill dam is raised in the downstream direction by placement of fill on top of the dam crest and downstream slope of the previous raise.

- Wide tailings beach to reduce seepage pressure on embankments, and promote subsurface drainage to the north with pond development against bedrock high to the southeast.
- Reduced tailings volume by using thickening methods or additional pumping capacity.
- Foundations to be placed on competent bedrock for increased stability.
- Each dam lift to undergo a thorough safety review, and adjusted as necessary.
- Dry closure methods to improve the stability for permanent in-place closure, with a closure cover design that would minimize infiltration.
- Monitoring performed during construction, operations, closure, and post-closure.

Pyritic TSF. The pyritic TSF would be designed to impound the pyritic tailings and potentially acid-generating (PAG) waste rock, and would include a continuous embankment around the northern, southern, and eastern sides with the following design and construction elements to prevent geohazard-related impacts:

- Fully lined, subaqueous storage cell during operations to minimize acid generation.
- Majority of the pyritic TSF in a single tributary valley.
- Liner protected with processed materials (sand and gravel) after installation to prevent damage from punctures or damage during waste rock placement.
- Liner installation completed in accordance with standard industry practices, and closely monitored.
- Water levels maintained for the life of the facility.
- Water levels and freeboard maintained to account for the inflow design flood, wave run-up, and wind set-up.
- Excess pond water controlled by pumping to the main WMP.
- Embankments prepared by removing overburden to competent bedrock.
- Tailings and waste rock moved into the open pit at closure.
- After closure, the liner removed and embankments graded/recontoured to conform to surrounding landscape and promote natural runoff and drainage.
- Monitoring included in all phases.

WMPs and SCPs. Two primary WMPs would be at the mine site (the main WMP north of the pyritic TSF, and the open pit WMP) to impound contact and open pit water, respectively. The SCPs would be downstream of the TSF embankments, and include those associated with the bulk TSF main and south embankments, and the pyritic TSF north, east, and south embankments. The facilities would include the following design and construction elements to prevent geohazard-related impacts:

- Fully lined to minimize seepage and risk of internal erosion.
- Rockfill embankments to promote stability.
- Main WMP embankment prepared by removing overburden to competent bedrock.
- Open pit WMP embankment design concept requiring potential weak foundation conditions encountered in the overburden materials (e.g., glacial lake deposits) to be excavated.
- Pond water volumes managed through reuse in the process plant, and treatment and discharge.

- Monitoring/seepage pumpback wells downgradient to detect and capture potential liner leakage.
- At closure, the WMPs to be removed and embankments graded/recontoured to conform to the surrounding landscape and promote natural runoff and drainage.
- Monitoring included during all phases.

Static Stability Analyses

Analyses were completed to evaluate the stability of the proposed embankments under static and non-seismic conditions. The following summarizes the static stability analysis. A more detailed discussion is presented in Appendix K4.15. The following major embankments and impoundments were analyzed:

- Bulk TSF main and south embankments
- Pyritic TSF north embankment
- Main WMP
- Bulk TSF main SCP
- Open pit WMP

The static stability analyses were completed using the computer program SLOPE/W. Input parameters were based on the results of field and office studies, and included the embankment configurations and assumed rockfill material, foundation materials, and stored materials. The results predicted the analyzed embankments would have a static factor of safety (FoS) between 1.7 and 2.0 (a static FoS of 1.1 or greater is considered stable). Additional static stability analyses would be completed in support of the final design.

As noted above, the Alternative 1 bulk TSF main embankment design would result in a serrated near-vertical upstream face at the dam crest for the upper 280 feet of the embankment that would partially rest on tailings. The potential for this configuration to liquefy during seismic events was reviewed by a panel of geotechnical experts during the EIS-Phase Failure Modes and Effects Analysis (FMEA) (AECOM 2018l). The stability analysis results do not rely on the strength of these materials, but rather on the strength of rockfill materials directly beneath and downstream of successive raises in the core zone and buttresses (Figure 2-8 and Figure K4.15-2). In other words, regardless of the low strength assigned to the tailings, the overall embankment did not fail in a downstream direction in the stability analysis. Therefore, the FMEA panel concluded that the likelihood of global instability of the buttressed centerline embankment design would be very low.

Seismic Stability Analysis

Active Surface Faults. The mine site is situated in a regionally seismically active area caused by the convergence of the Pacific and North American tectonic plates. The most significant seismically active geologic structure near the mine site is the Bruin Bay fault, which is situated about 70 to 80 miles to the east-southeast.

No mine facilities would be constructed on top of known active surface faults. As presented in Section 3.15, Geohazards, the closest potentially active fault to the mine site, the Lake Clark fault, is about 15 miles to the northeast. Recent mapping at the mine site and vicinity has not shown evidence of offset of surficial deposits along faults or lineaments in the area (Hamilton and Klieforth 2010; Haeussler and Waythomas 2011; Koehler 2010). This conclusion is further supported by Light Detection and Ranging (LiDAR) data that were collected in 2004 in the mine site area. The LiDAR-derived image was reviewed for possible indications of fault-related movement in surficial deposits. No lineaments were observed that suggest possible Quaternary fault-related movement southwest of the mapped termination (AECOM 2018m).

More detailed discussion regarding seismic sources and hazards in the greater project area is presented in Section 3.15, Geohazards, Appendix K3.15, and Appendix K4.15.

Seismic Hazard Analyses. The TSF embankments at the mine site would be regulated as Class I (high) hazard potential dams under the Alaska Dam Safety Program (ADSP) draft dam safety guidelines (ADNR 2017a; PLP 2017). Based on these draft guidelines, two levels of design earthquake must be established for Class I dams:

- *Operating Basis Earthquake* (OBE) that has a reasonable probability of occurring during the project life (return period of 150 to more than 250 years), for which structures must be designed to remain functional, with minor damage that could be easily repairable in a limited time. In other words, minor damage within allowable design criteria may be sustained at the TSF embankments following an OBE earthquake.
- *Maximum Design Earthquake* (MDE) that represents the most severe ground shaking expected at the site (return period from 2,500 years up to that of the Maximum Credible Earthquake [MCE]), for which structures must be designed to resist collapse and uncontrolled release.

The OBE can be defined based on probabilistic evaluations, with the level of risk (probability that the magnitude of ground motion would be exceeded during a particular length of time) being determined relative to the hazard potential classification and location of the dam (ADNR 2017a). The MDE may be defined based on either probabilistic or deterministic evaluations, or both (ADNR 2017a).

Ground-shaking from earthquakes is typically presented in terms of PGA, measured as a fraction (or percent) of gravity (g), which represents the intensity of an earthquake as it is applied to a structure, such as the TSF embankments. The degree of ground shaking and structural damage expected is related to earthquake magnitude, distance from active faults, and duration of shaking. For example, small local earthquakes may cause more ground shaking than large, more distant earthquakes; and large distant earthquakes with a lower PGA but longer shaking duration may cause more damage than smaller nearby earthquakes with a higher PGA. As such, the selected OBE or MDE may be based on more than one earthquake scenario. A number of potential earthquakes were evaluated in the probabilistic and deterministic seismic hazard analyses (see Appendix K4.15) to develop the OBE and MDE.

A conservative OBE corresponding to a return period of 475 years was adopted for the Pebble TSF designs (Knight Piésold 2013). Based on this return period, the estimated PGA has been determined to be 0.14g (or 14 percent of gravity acceleration). The design earthquake magnitude associated with this level of ground shaking includes:

- A magnitude 7.5 earthquake determined based on probabilistic seismic hazard analysis which considers a combination of potential faults (Appendix K4.15, Table K4.15-7) (Knight Piésold 2013; Wesson et al. 2007).
- A magnitude 9.2 earthquake on the Alaska-Aleutian megathrust (having the same PGA of 0.14g because it is more distant) based on deterministic seismic hazard analysis (Appendix K4.15, Table K4.15-8).

The MCE was selected as the MDE for the Pebble TSFs (KP 2013). Earthquake magnitudes and ground shaking associated with the MCE considered in TSF embankment design include:

- A magnitude 6.5 shallow crustal earthquake from an unknown fault assumed to occur directly beneath the mine site, with a PGA of 0.61g.
- A magnitude 8.0 intraslab subduction earthquake (similar to the source of the magnitude 7.0 Anchorage earthquake on November 30, 2018), with a PGA of 0.48g.

- A magnitude 7.5 earthquake on the Lake Clark fault, with a PGA of 0.29g.
- A magnitude 9.2 megathrust earthquake with a PGA of 0.14g.

Appendix K4.15 provides further discussion of the seismic sources and probabilistic and deterministic evaluations completed for the project to evaluate potential ground shaking associated with these earthquakes. The seismic hazard analyses would be updated in final design to support ADSP design and reporting requirements, incorporating best practices for analysis published since the Knight Piésold (2013) study (Bozorgnia et al. 2014) and updated USGS ground motion data as available (PLP 2018-RFI 008c).

Seismic Deformation Analysis. A pseudo-static deformation analysis was completed to predict the response of the largest embankment (the bulk TSF) to a seismic event, based on the OBE, as well as MCEs from four potential seismic sources (faults) with magnitudes ranging from 6.5 to 9.2 (Appendix K4.15). Predicted displacements in the embankment were estimated to be negligible for the OBE, and on the order of 4 to 5 feet of horizontal displacement and crest settlement under MCE loading conditions. The displacements were not large enough to truncate the filter or transition zones, and would not affect the functionality of embankment. The results were used to design the minimum freeboard requirements for the bulk TSF embankments.

The deformation and settlement analyses would be updated as part of the ongoing design of the TSFs and other embankments. Additional detailed modeling, including analyses using Fast Lagrangian Analysis of Continua (FLAC) numerical modeling software, would be completed during detailed design of the facilities to better define embankment displacements.

Summary of Stability Effects. The magnitude of direct effects on mine embankments from earthquakes, floods, static loading, slope failure, and foundation conditions could range considerably. Effects would not be measurable where designs are adequate for expected geohazards, such as moderate earthquakes, large precipitation events, or known unstable foundation conditions that are removed in construction. In terms of duration, effects could include damage that would be repairable in the short term (e.g., months) in the event of an OBE; or in the event of an MDE, effects could range up to damage that would not be easily repairable, but would not be expected to lead to structural collapse or uncontrolled release of contaminated materials. Assuming that facilities are planned, designed, constructed, operated, maintained, and surveilled as proposed and in accordance with ADSP guidelines (ADNR 2017a), in terms of extent, potential damage to facilities and indirect effects on the environment would be expected to remain within the footprint of the mine site. In addition to ADSP oversight, PLP would also establish an independent review board to review embankment designs and stability analyses as engineering analysis progresses (AECOM 2018k).

The duration of effects would vary depending on the facility and likelihood of geohazard occurrence. In the case of earthquake damage that would be easily repairable, impacts would be infrequent, but not longer than the life of the mine for facilities that would be removed at closure (e.g., embankments at the pyritic TSF). Impacts could occur in perpetuity for structures that would remain in place (e.g., bulk TSF embankments). Based on the conceptual designs, and assuming that current standard of engineering practice would be followed, the likelihood of global instability of the major embankments was considered to be very low (i.e., less than 1 in 10,000 probability) by geotechnical experts in the EIS-Phase FMEA (AECOM 2018l). Indirect effects on other downstream resources in the unlikely event of an embankment spill or release are discussed in Section 4.27, Spill Risk.

Open Pit Slopes

Numerical modeling was completed to predict the stability for three sections of the open pit walls with known weak rock conditions (Appendix K4.15, Figure K4.15-10). As described in Appendix