Baseline Investigations and Preliminary Design for an In-Pit Tailings Storage Facility, El Gallo Mine, Sinaloa

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Abstract

Minera Pangea recently completed a feasibility study (FS) for an in-pit tailing storage facility (IPTSF) that will receive tailings from reprocessing of approximately 10 million tonnes of heap leach material (HLM). The HLM from the existing El Gallo heap leach pad would be reprocessed through a plant and then pumped to the IPTSF. The FS included a range of characterization and engineering design studies to determine the behaviour and potential environmental impacts associated with the IPTSF, including tailings deposition and consolidation; baseline hydrogeology and geochemistry; a groundwater control system and closure design.

The El Gallo gold mine is located in the western foothills of the Cordillera Sierra Madre, east of the city of Guamuchil in the State of Sinaloa. The deposit is a low sulfidation epithermal vein system hosted in Late Cretaceous-Tertiary volcanic rocks, principally andesites. The climate is semi-arid with monsoonal rains during the wet season. Groundwater flow is controlled by fractures that run through and under the pit. The pit is currently a terminal sink, with evaporation exceeding groundwater inflow plus runoff into the pit. Geochemical characterization of the detoxified tailings indicate that are non-acid generating. Analysis of the tailings supernatant and leach solution indicate that neither would have a significant impact on groundwater quality.

A key aspect of the proposed IPTSF will be an underdrain system in the floor of the pit, which will reduce pore pressures and maintain the existing cone of depression in the groundwater surface around the pit during operation and closure, and aid in tailings consolidation by facilitating drainage (McDonald and Lane 2010) . Tailings supernatant will be recovered using a floating pump on the surface of the tailings pond. Tailings solution recovered from the surface of the tailings as well as the mixture of groundwater and tailings solution captured by the pit's underdrain system will be reused in the process plant.

The El Gallo IPTSF presents an efficient and cost-effective engineered solution for tailings storage that benefits both Pangea and the community by: 1) Mitigating the potential impacts associated with the heap leach facility and evaporative groundwater consumption by the open pit; 2) Eliminating the potential

impacts of a surface tailing storage facility (such as dam failures) and associated post closure management of a retention structure; and 3) Providing an economical solution for the storage of process tailings to enable continued operation for Pangea.

Introduction

The El Gallo gold mine in Sinaloa, Mexico provides an excellent example of the process of evaluation, testing and design for an IPTSF. The mine has 10 million tonnes of HLM that is undergoing cyanide leaching, but the gold recovery is lower than expected (40%) due to the mineralogy of the ore and method used to place the ore on the leach pad. Sufficient gold remains in the HLM to profitably reprocess the ore through a new 5,000 tonnes/day processing plant, which would include grinding, cyanide in leach, carbon sorption and cyanide detoxification. Tailings from the plant would be discharged into the mined-out Samaniego pit in such a way to maximize water reclaim and tailings consolidation. An underdrainage system would be installed to capture groundwater entering the base of the pit and water from tailings consolidation. Supernatant water liberated from the tailings slurry would be recovered at the surface of the IPTSF via a pontoon-mounted pump. The proposed IPTSF would have approximately 8.0 million cubic meters (Mm^3) of storage volume. This equates to a tailings storage capacity of 12 to 14.4 million tonnes, assuming a range of tailings in-situ dry densities between 1.5 and 1.8 tonnes per cubic meter (t/m^3).

As with any mine development project or significant change in mining operations, a wide range of tasks were performed to evaluate site conditions and develop the technical specifications of the IPTSF and support the permitting process, including

- Design of a new processing plant.
- Hydrogeologic characterization of the Samaniego pit.
- Geochemical characterization of the tailings and pit walls.
- Design of the tailings fluid recovery and groundwater management system.
- Geotechnical testing of the tailings material.

Advantages of an IPTSF

Recent high-profile tailings dam failures in British Columbia (Mt. Polley), Bello Horizonte, Brazil (Córrego de Feijão) and Chihuahua, Mexico (Cieneguitas) have raised the level of awareness of both mining professionals and the general public regarding the reputational, environmental, financial and operation risks associated with traditional tailings storage facilities (TSF) that employ earthen retaining structures. Alternatives to traditional TSFs include disposal as a paste in underground workings and disposal in mined-out pits. The use of IPTSFs is not new but is gaining increased acceptance for disposal of mine waste (tailings, waste rock and processing solutions), particularly if the material is acid generating. IPTSFs can be an attractive alternative to TSFs, within the following constraints (Arcadis 2015 and Lane 2005):

- A locally available pit that will not cover or "sterilize" remaining mineral resources.
- Pit filling above active underground mines are considered unsafe.
- The amount of waste rock and tailings produced from a pit does not usually fit back into the pit, requiring dual disposal scenarios in some cases.
- Local hydrogeologic conditions are a critical factor in the selection and design of an IPTSF.
- The feasibility, cost and design of an IPTSF depends significantly on the leaching potential of mobile contaminants from the material placed in the pit.

Despite these constraints, an IPTSF can be an attractive engineering solution for tailings storage that can benefit the mine and community during operation and closure of the mine. These benefits include (ARCADIS 2015):

- Isolation of potential reactive mine waste in an anoxic environment, which inhibits the formation of acid and metal leaching.
- Reduce or eliminate the necessity of maintaining engineered structures.
- Improved social license and regulatory acceptance of the mining activity by restoring original landform and function.
- Potential for reduced closure costs. In this case, the IPTSF will eliminating the need to close a heap leach facility (by reprocessing the ore) and minimize long-term closure costs.
- In some cases, returning the pit site to its original use (e.g. grazing).

Site background

The El Gallo gold mine is owned and operated by Minera Pangea, the Mexican subsidiary of McEwen Mining. The mine is in the western foothills of the Sierra Madre Mountains in the state of Sinaloa (Fig. 1). The mine operation consists of five open pits (Samaniego, San Rafael, Sagrado Corazón, Central and Lupita), a heap leach pad, and a carbon adsorption, stripping and electrowinning circuit. The proposed IPTSF would backfill the Samaniego pit, taking advantage of the gravity gradient from the proposed processing plant downhill to the pit.

Average annual rainfall is 865 millimetres (mm), occurring in well-defined wet and dry seasons. Precipitation during the wet season (June through October) averages 150 mm per month. During the dry season (February to May or June), rainfall averages 11 to 17 mm of precipitation per month. The estimated average annual evaporation is 1,818 mm (Solum 2018).

The El Gallo mine is hosted by Late Cretaceous-Early Tertiary volcanic rocks of the Lower Volcanic Series composed of andesitic flows and tuffs. The ground surface is covered with a thin veneer (1 to 3 m) of soil and alluvium, underlain by weathered andesite. The ore deposit is classified as a low sulfidation epithermal vein deposit (LSEVD). Mineralogical analysis of the ore from the Samaniego pit is characterized by quartz (56.3%), adularia (29.3%), kaolinite (7.9%) and minor hematite, chlorite, albite and calcite. Gold mineralization in the El Gallo mine area occurs along two distinct structural trends, a northwest trend which hosted the San Rafael and Samaniego deposits and a northeast-striking structural trend that hosted the Sagrado Corazón, Central and Lupita deposits.

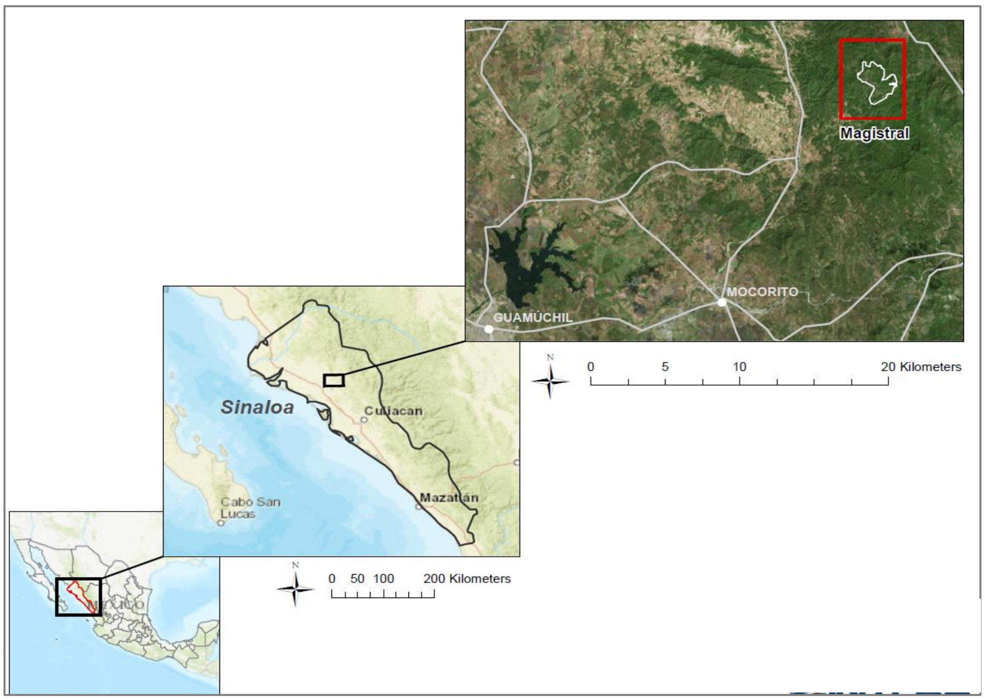

Figure 1: El Gallo Gold Mine Location

The host rock presents extensive propylitic alteration and slight silicification near the margins of the principal structures. Multiple phases of hydrothermal activity deposited quartz with massive, banded, crustiform and colloform textures, which fills structures and produced stockwork zones in the dominant structures. The dominant alteration type directly associated with mineralization is silicification in the form of breccia cement, pervasively silicified breccia clasts, and, locally, pervasively silicified wall rock and quartz veining (PAH, 2011). Sulfide minerals occur at concentrations of less than 1% (by weight) but have been observed at concentrations up to 3%. The main sulfide minerals are sphalerite, galena, pyrite, and chalcopyrite (PAH, 2011).

Groundwater flow in the vicinity of the Samaniego was measured by the mine operator using a network of shallow wells. Groundwater appears to flow to the west from the surface water divide approximately one kilometer east of the pit and follow topography to the west and northwest (Fig. 2). Limited groundwater flow into the pit and the high evaporation rate produces a terminal pit lake approximately 120 meters below the local groundwater surface with a steep cone of depression.

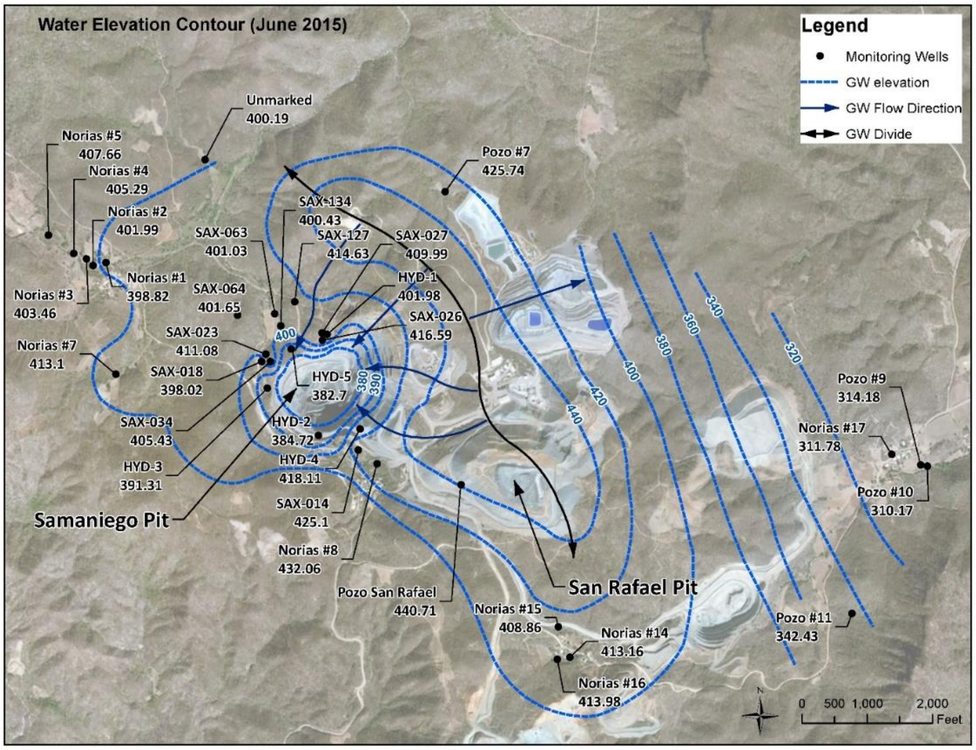

Figure 2 Regional Groundwater Flow Map, El Gallo Mine

Methodology

Geochemical Investigation

Two key geochemical elements were integrated into the engineering design of the IPTSF: the potential for acid generation and leaching of metals due to oxidation of sulfide minerals in the pit wall rock and tailings, and the chemistry of the tailings solutions that might leach from the pit into groundwater.

Six samples of the detoxified tailings samplers were generated from composited HLM material. The samplers were processed by Kemetco Research Inc. of Richmond, Canada, using a bench-scale version of the proposed cyanide leaching, carbon in pulp extraction and cyanide detoxification (SO_2/O_2 method). The cyanide destruction test was designed to achieve a proposed discharge limit of 20 mg/L WAD cyanide. Samples at 40% solids were used for supernatant analysis. Tailings samples for geochemical analysis were filtered by Kemetco and then air dried prior to analysis.

The leaching potential of detoxified tailings in the IPTSF was evaluated by geochemical analysis of the solids (6 samples), the tailings supernatant solution (5 samples) and the leachate produced from interaction of the tailing solids with water (3 samples). Geochemical analysis of tailings solids included Acid-Base Accounting (ABA), paste pH, total elements, sulfur speciation, carbon speciation, mineralogy and neutralization generation potential (NAG) tests. Leaching potential of the tailings was evaluated using the meteoric water mobility procedure (MPMP) specified in SERMARNAT NOM-157-2009 (NOM-157) and the modified ASTM D3987-85 (bottle roll) procedure specified in SERMARNAT-NOM-141-2003. Leachate samples and supernatant were analyzed for dissolved and total metals, major ions (chloride, fluoride and sulfate), cyanide species, acidity, ammonia, pH, and alkalinity. Samples were analyzed by SGS and ALS in British Columbia. Confirmation analysis of selected samples was performed by ALS Indequim in Monterrey, Mexico to comply with requirements for data from a Mexican certified laboratory.

Geochemical evaluation of potentially reactive surfaces and weathering products in the pit wall was performed using paste pH of efflorescent salts (11 locations) and two samples of pit wall seeps.

Water Recovery Systems

The engineering design of the IPTSF underdrain collection system (UCS) was undertaken by Tierra Group International of Salt Lake City from conceptual designs provided by L&MGSPL (Cowaramup Western Australia). The surface water recovery system is design to remove up to 85% of the water from the slurry allowing self-weight consolidation of the tailings mass, thereby reducing the time required to achieve the highest density possible during the filling of the pit. The UCS serves the following purposes:

- Assist with consolidation through efficient water removal from the base of the pit.
- Reduce pore pressure in the base of the pit by maintaining the cone of depression around the pit, minimizing the migration of tailings solutions or weathering products into the surrounding aquifer.

Monitoring/recovery bores located around the pit's perimeter will provide secondary control on water movement from the pit via monitoring and pumping.

Hydrogeological Investigation

The baseline hydrogeological study was carried out during May, June, and July of 2018. The study included an extensive field investigation carried out in and around the Samaniego pit, which included:

- Drilling five borings and performing packer (Lugeon) type permeability tests or tests at selected intervals where the borings intersected geologic structural features with potential hydraulic paths through or below the Samaniego pit.
- Injection (Lefranc) tests in six existing exploration boring.
- Completion of multi-level vibrating wire piezometers in three of the test holes.
- Observations in and around the pit of groundwater flow (locations, rates and structural controls).

- A water balance for the Samaniego pit to estimate groundwater inflow.

The results of the hydraulic tests provided data to quantitatively calculate the in-situ permeability of the fractured rock mass. The packer data provided fracture specific measurements of K while the injection test provide bulk rock values. The aquifer test data were analysed using the nSIGHTS (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator) numerical code developed for Sandia National Laboratories (Geofirma and INTERA, 2011). The nSIGHTS code uses non-linear parameter estimation methods to find the optimal values of the model fitting parameters (typically hydraulic conductivity, specific storage, formation pressure, skin radius, and skin hydraulic conductivity) that provide the best match to the observed test data.

Geotechnical Testing

An extensive geotechnical characterization program was undertaken to: evaluate the tailings storage capacity (a function of final density); the amount and timing of tailings dewatering; the total settlement of the tailings stack during operation; and the magnitude and time for the final settlement. Testing on the final size distribution for tailings (60% smaller than 75 microns) was performed by the University of Alberta. A standard suite of geotechnical tests was performed on the tailings, including liquid limit, plasticity, density and permeability. Specialized tests including large-strain consolidation and centrifuge testing were performed to generate data on the total settlement of the tailings stack during operation.

Permitting

The primary Mexican regulation governing the evaluation, construction, operation and closure of a TSF is NOM-141. One of the challenges with the permitting of the El Gallo IPTSF is that NOM-141 was specifically written for traditional TSFs, so many of the NOM-141 requirements do not apply to an IPTSF. Only one other IPTSF had previously been permitted in Mexico, at the Agnico Eagle Pinos Altos mine, which will store paste tailings above an active underground mine. For the El Gallo IPTSF a highly collaborative permitting strategy was developed between Pangea staff and the Secretariat of Environment and Natural Resources (SEMARNAT) regulators that included presentations, site visits, and case studies of other IPTSFs. The permit was issued by the Sinaloa SEMARNAT office on August 25th, 2019.

Results

Geochemistry

The neutralization potential ratio (NPR) provides an indication of the acid generation potential of a waste material based on the ratio of neutralization potential (NP) to acid potential (AP). The Mexican NPR criterion for potentially acid generating (PAG) tailings is 1.2. Material below this value is considered to be potentially hazardous, requiring additional characterization and a waste handing plan. Data from the ABA tests were also compared to NPR criteria recommended by MEND (2009), which specifies a NPR of 2 as the criterion for non- PAG material, and a range of NPR between 2 and 1 to define material that has uncertain acid generating potential and might require additional characterization. Figure 3 shows the results for the El Gallo tailing samples. The average NPR for the tailings samples is 2.4, which is considered non-acid generating. These results were confirmed by the NAG tests, which produced a NAG pH after reaction of 6.60 and 6.61. A NAG pH above 4.5 is considered non-acid generating. The average concentration of sulfide minerals was 0.21% by weight (equivalent to an AP of 6.56 kg $CaCO_3$/ton).

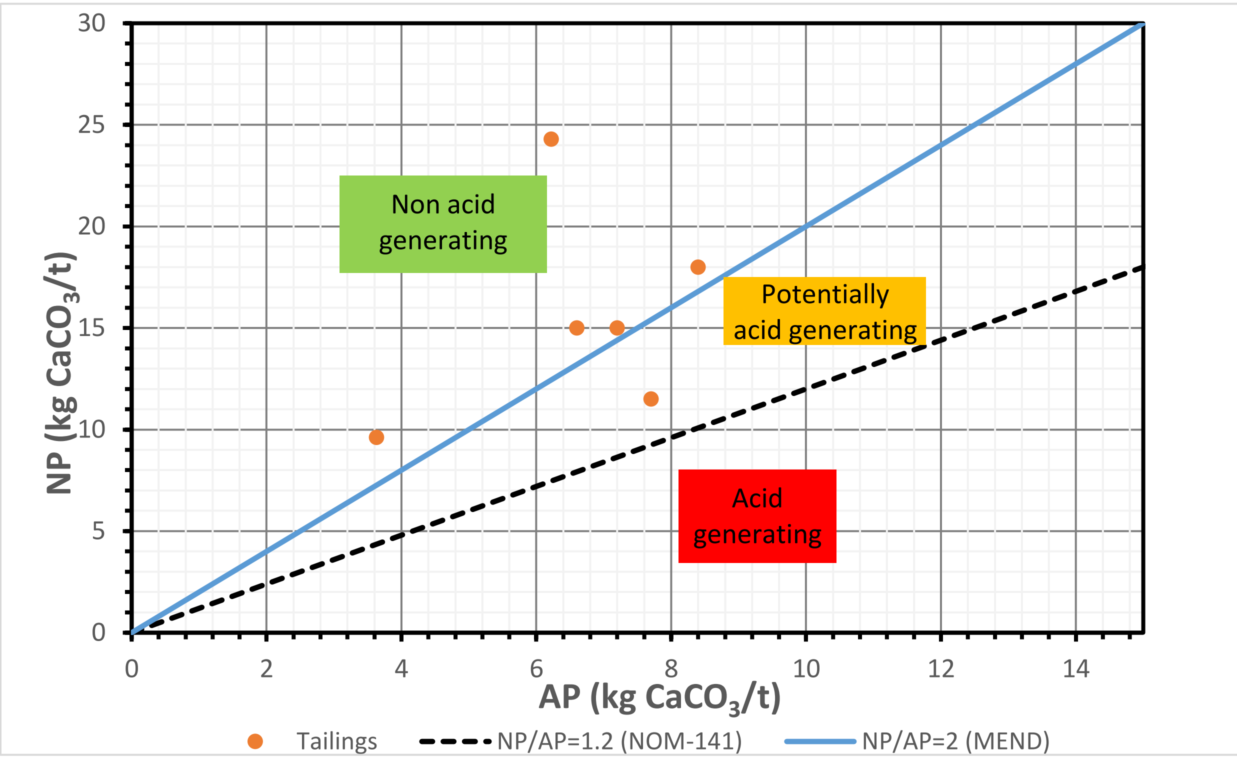

Figure 3: Neutralization Potential vs Acid Potential for El Gallo Tailings Samples

Additional results for the geochemical evaluation include:

- Geochemical evaluation of the paste pH of efflorescent salts in the Pit wall at 11 locations resulted in one sample with low pH (2.83). The remaining 12 samples were all above 7.5.
- Concentrations of soluble metals in leachate samples did not exceed the NOM-141 criteria.
- Cyanide concentrations in the supernatant immediately after the detoxification procedure ranged from 0.5 to 4.4 mg/L. WAD cyanide ranged from 1.13 to 2.52 mg/L while free cyanide was generally under 1 mg/L. The cyanide concentrations in the pore space of the tailings would be

expected to lower than the supernatant concentrations due to photochemical dissociation of iron cyanocomplexes and volatilization (Johnson, 2015).

- Cyanide concentrations in leachate samples were low, with total concentrations of 0.057 and 0.14 mg/L. WAD cyanide concentrations were below the reporting limits of 0.008 and 0.01 mg/L,

The available data indicates that the tailings would be non-acid generating and unlikely to leach constituents that would impact the aquifer.

Hydrogeology

Results of the aquifer tests indicate that the majority of fractures present in the vicinity of the Samaniego pit have a low hydraulic conductivity (K), with most of the test intervals varying from 1E-06 to 1E-09 m/s. Higher transmissivity (K values <1E-04 m/s) correspond to the unit of conglomerate and weathered andesite near the surface and above the maximum planned level of the IPTSF. Higher values of K (up to 2.4E-2 m/s) were measured below the pit. Results of the pit water balance indicate that groundwater infiltration into the pit aquifer will range from 190 to 345 m^3/day (2.2 to 4 L/second).

The conceptual groundwater model envisions a fracture flow system with low hydraulic conductivity near a groundwater divide with a gentle gradient and limited recharge. Groundwater flow into the pit is primarily vertical from the higher K structures under the pit. The sum of groundwater flow into the pit and runoff during the rainy season is less than evaporation from the pit, resulting in a terminal pit lake with a surface more than 100 m below the local groundwater table.

Underdrain Collection System

The proposed UCS is an industry standard in TSF design for tailings consolidation and seepage collection, and will consist of a blanket drain installed at multiple elevations within pit's floor with a collection sump and pumps to return the mixture of supernatant and groundwater to the processing plant. (Fig. 4) The blanket drain will consist of a network of perforated high-density polyethylene (HDPE) pipes covered with gravel wrapped in high permeability, non-woven geotextile with a pore size of 0.15 mm or smaller. The mass of the geotextile will range from 400 to 800 g/m2, depending on the required permeability and flow rate. Water collected by the UCS will be directed to a sump established in the pit's lowest point, where it will then be pumped to the processing plant for reuse.

From the pit's crest two solid wall HDPE reclaim sleeves will run along the pit wall and penetrate the sump, allowing reclaim pipes and pumps to be lowered into the sump from the crest of the facility through the sleeves. The two reclaim pipe sleeves also provide redundancy for the UCS should one of the lines become blocked or damaged. The reclaim sleeves will be installed along the pit's western wall using rock bolts and anchors.

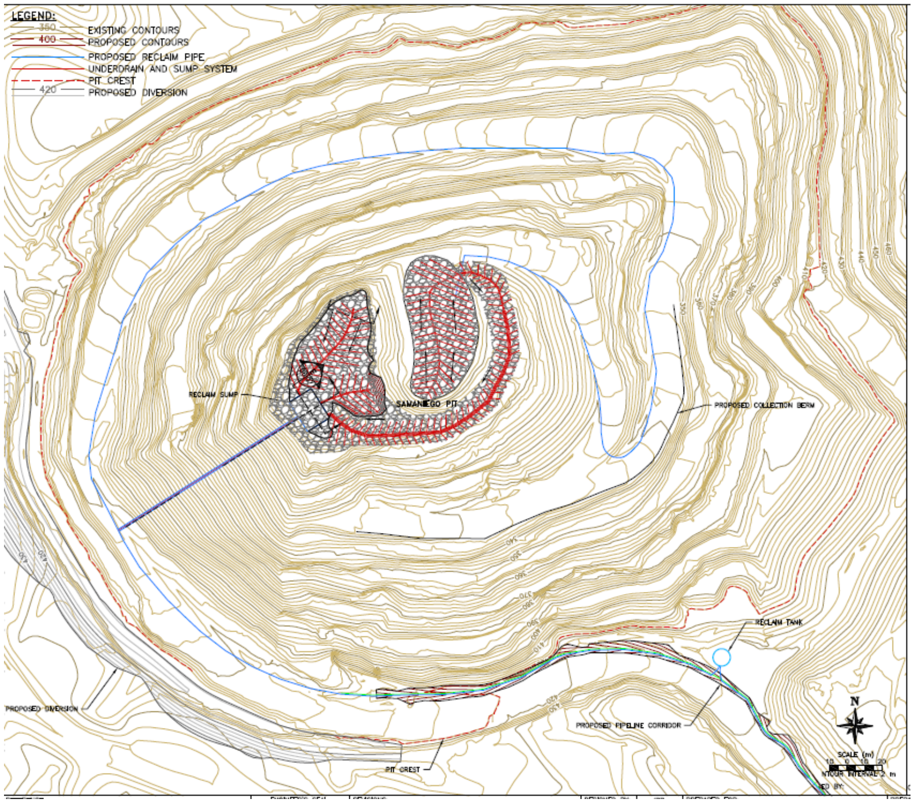

Figure 4: Proposed pit underdrain

Tailings Consolidation

A summary of the various results obtained from the classification and density testing (with no loading applied) executed by University of Alberta of Edmonton Canada is presented in Table 1. Tests show low plasticity to no plasticity, so secondary settlement is not a consideration post closure. Creep settlement may occur over time post closure, but this settlement will be a small fraction of the total settlement during operation which the PLAXIS 2D model indicates as 8.45 m in Year 1 of Operation and 1.21 m in Year 8 of Operation.

The consolidation tests demonstrate that a low void ratio (high in-situ dry density and very low permeability) can be achieved during the operation of the IPTSF, provided water is continually removed from the facility. The centrifuge testing simulated a tailings depth of approximately 37 m, with final void ratio of 0.71, residual moisture content of less than 25% and dry density of 1.62 t/m^3. The actual pit depth to be filled with tailings, is estimated to be between 127 m to 135 m. An extrapolation of the trend for the void ratio and dry density from 37 m to 120 m demonstrate that the void ratio would be less than 0.45 and the dry density would increase to at least 1.8 t/m^3. The implied permeability at this range of void ratios is 3.03 x 10^{-9} m/sec and 7.16 x 10^{-10} m/sec.

Table 1: Summary of Geotechnical Test Results

Test	Results
Particle size distribution (% passing 75 microns)	60 (laser sizing)
Liquid Limit (%)	Non-Plastic
Plastic Limit (%)	Non-Plastic
Plasticity Index (%)	Non-Plastic
Soil Particle Density (t/m^3)	2.77
Estimated permeability (with 500 kPa loading) from large strain consolidation test (m/s)	5.12 x 10^{-7}
Initial dry density (t/m^3) at 50.4% solids with void ratio of 2.73	0.7
Settled dry density (t/m^3) from 500 kPa with void ratio of 1.04	1.4
Final average dry-density (t/m^3) Effective Stress 350 kPa with void ratio of 0.78	1.6
Implied permeability m/s below 37 m based on centrifuge test	10^{-9} to x 10^{-10}
Predicted post closure settlement (m) based on centrifuge test and PLAXIS 2D analysis	1.0
Estimated period for post closure consolidation (years)	8

Closure

Once the tailings have reached the maximum planned elevation within the IPTSF, the facility will be covered to prevent erosion as well as rainwater infiltration. The cover will consist of a compacted layer of material with low hydraulic conductivity overlain by layer to promote the growth of vegetation. The cover will be domed (higher in the center) to facility drainage and account for final compaction. The UCS will continue to operate as long as the tailings continue to consolidate, to maintain the cone of depression around the pit.

Conclusions

Geochemical studies of the detoxified tailings that will be placed in the Samaniego pit indicate that they have a very low average sulfide content (0.21%) and will not be acid generating or leach metals. Leaching tests and analysis of the supernatant indicate that residual solutions would not impact groundwater quality.

The limited groundwater flow into the pit via fractures (K less than 1E-7 m/s) and lower K of the consolidated tailings (10E-8 to 10E-9 m/s) will minimize potential groundwater flow through the mass of consolidated tailings. The contrast in Ks between the fractures and the tailings would lead to preferential flow around the tailings rather than through it (ARCADIS 2015)

The geotechnical and hydrogeological testing clearly demonstrate that a key factor in the operation of the IPTSF is the water recovery system (pumps and piping) which will have sufficient capacity to remove water at a rate which will expedite the consolidation of the tailings and prevent migration of any tailings solutions from the pit by maintaining the cone of depression in the groundwater table. Emplacement of fine-grained tailing in the pit would seal potentially reactive surfaces in the pit walls. The very low permeability of the tailings would limit oxygen diffusion and advection of water, two of the key components in the generation of acid drainage.

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