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Engineering and reclamation of the Holden Legacy Mine — advancing the state-of-practice for mine closure

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Abstract

Rio Tinto is reclaiming an abandoned copper mine in one of the most isolated places in the continental U.S., located near Lake Chelan in the remote reaches of north-central Washington State. The Holden Mine was one of the largest operating underground copper mines in the U.S.; the mine was developed and operated between 1937 and 1957 and produced over 90,000 tonnes of copper, as well as zinc, silver and gold. Over the life of the mine, nearly 100 km of underground tunnels had been excavated and 7.6 million tonnes of mill tailings placed on U.S. National Forest lands near Railroad Creek. Although Rio Tinto never owned or operated the mine, they are managing and funding a several hundred million dollar clean-up to prevent future water and soil contamination and to restore the former mine site under the United States Environmental Protection Agency Superfund process. Adjacent to the mine is a former man camp, now home of the Holden Village Inc., a religious community that hosts 5,000 to 6,000 visitors each year. Engineering the Holden Mine remedial design required development of an integrated system of mine closure components including: infrastructure improvements, surface water and sediment management, slope stability improvements, surface and groundwater collection and treatment, mill demolition, and restoration to re-establish vegetation consistent with that of the surrounding forest. This paper addresses these topics and includes information on the design criteria and objectives, pre-design investigations and evaluations, and a summary of the design for each remedial component. The paper concludes with the project successes and lessons learned from engineering the remedial design. The first in a series of technical papers, this paper provides the mine closure community an overview of the innovative design and construction techniques that have been applied at the Holden Mine with the goal of further advancing the state-of-practice for mine closure and remediation at other sites.

1 Introduction

1.1 Site location and history

The Holden Mine is a former underground copper mine that was developed and operated by the Howe Sound Mining Company (Howe Sound) from 1938 to 1957. The mine is located in the northwestern U.S. in north-central Washington State near Lake Chelan (Figure 1). The former mine site is being reclaimed by Rio Tinto Corporation; although Rio Tinto never owned or operated the mine, they are managing and funding a several hundred million dollar clean-up to prevent future water and soil contamination and to restore the former mine site under the United States Environmental Protection Agency (US EPA) Superfund process. The former mine included an onsite mill and a nearby housing complex for the miners. Howe Sound developed the mine as a series of near-horizontal drifts and tunnels, interspersed with stopes and shafts that connect different mine levels underground. The tunnels that were excavated to develop the mine total nearly 100 km in length.

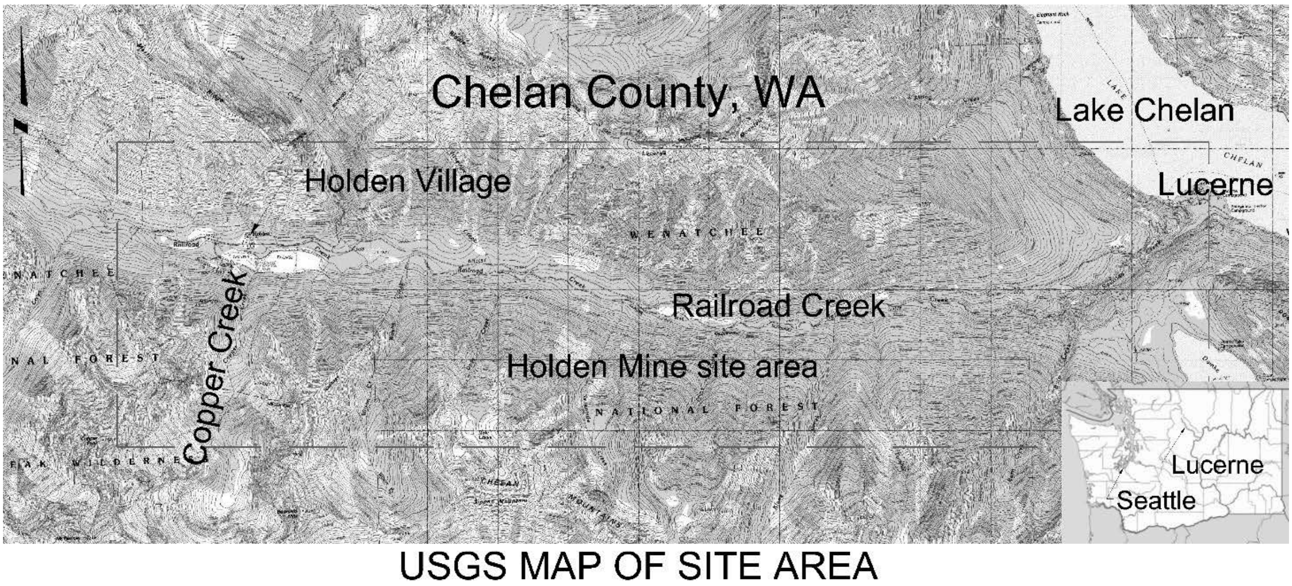

Figure 1 United States Geological Survey (USGS) map of site location

During development of the underground workings, Howe Sound removed more than 230,000 m^3 of waste rock from the tunnels and deposited this material in two waste rock piles. Ore was processed from the mine in the onsite mill to produce a copper concentrate that was shipped off site for smelting. Roughly 10 million tonnes of tailings were produced as a byproduct of the milling operation, most of which were deposited in three large impoundments directly south of and adjacent to Railroad Creek. The tailings contain reactive minerals, most notably iron sulphide (pyrite). Howe Sound relocated portions of Railroad Creek northward to make room for construction of the tailings impoundments. The general site features are shown in Figure 2. Howe Sound closed the mine in 1957. In 1961 the property was transferred to Holden Village, Inc. (Holden Village), a not-for-profit corporation that maintains a year-round community and operates an interdenominational religious retreat in the former miners' town. With the exception of the patented private land, the remainder of the site is on National Forest lands and is administered by the U.S. Forest Service.

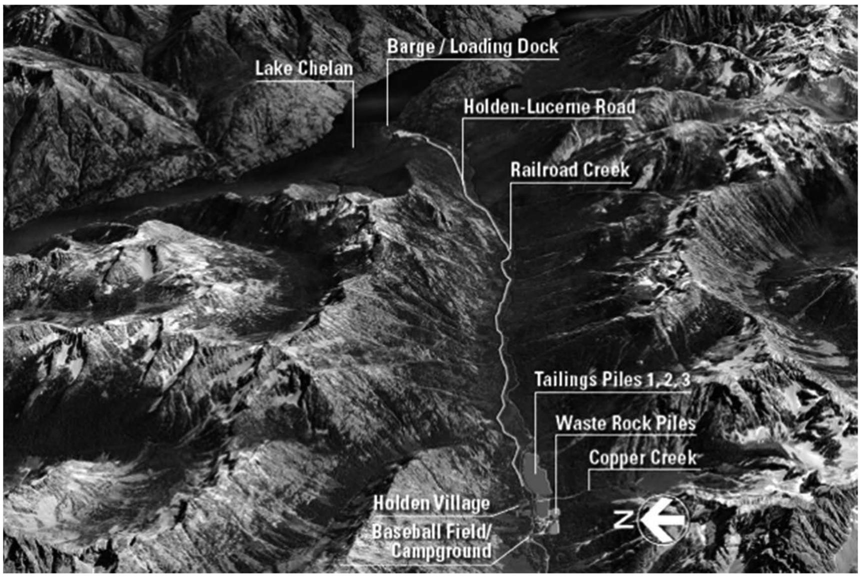

Figure 2 General site features

The mine is remote. It is only accessible by boat or float plane from Chelan, Washington, up Lake Chelan to Lucerne, nearly 40 km. Vehicle access from Lucerne to the mine is provided through a 17.5 km long, winding gravel road that climbs 640 m in elevation.

1.2 Physical setting

The Holden Mine is located on the eastern slopes of the Cascade Mountain Range in north-central Washington State at an elevation between 975 and 1,050 m above mean sea level. Holden Mine was developed adjacent to Railroad Creek, approximately 28.5 km upstream from the creek's outlet into Lake Chelan at Lucerne. Railroad Creek lies in a glacial u-shaped valley carved into the igneous and metamorphic bedrock with steep-sided slopes (Figure 2).

The mine workings were developed to extract ore from zones of metamorphic schists and gneisses on the south side of the valley. The valley bottom and lower sidewalls have been covered with soil of glacial origin, reworked glacial sediments, and alluvium transported and deposited by Railroad Creek. The tailings and waste rock piles overlie the glacial soil and alluvium. The climate in the vicinity of the site is characterised by hot, dry summers and mild to severe winters. Average monthly temperature varies from highs in the 30s°C in July and August to extreme low temperatures, well below 0°C in January. Average temperatures are generally below freezing between the months of November to March. Precipitation in the region can be highly variable due to strong geographic effects resulting from the mountainous terrain. The average annual precipitation of 991 mm falls mainly as snow. The average annual snow fall is about 6.9 m.

1.3 Description of primary reclamation components

The major components of the site reclamation are as follows as shown in Figure 3:

Stabilisation and regrading of Tailings Piles 1, 2, and 3: Tailings Pile 1 (TP-1), Tailings Pile 2 (TP 2), and Tailings Pile 3 (TP-3) range between 12 and 37 m high and extend over about 0.3 km² immediately adjacent to, and south of, Railroad Creek ①. The tailings contain reactive minerals, most notably iron sulphide (pyrite). The iron sulphide reacts with oxygen and water to produce soluble iron and sulphate; a reaction that is accompanied by the production of acidic (low pH) conditions and increased solubility of a number of metals. The slopes and foundations of TP-1, TP 2 and TP-3 were improved to provide greater stability under steady state and seismic conditions. This included using earth-moving equipment to regrade the slopes (to be less steep), contour the surfaces to promote maximum run-off and reduce infiltration, and constructing benches for erosion control and buttressing. Strengthening the zone of overbank deposits, on which the tailings piles were built, was a critical element to improving their stability. The overbank deposits have low shear strength and could liquefy during a seismic event. The foundation improvements included constructing jet grouted in situ columns of soilcrete. Following regrading and stabilisation, the tailings piles will be covered with a layer of soil and re-vegetated.

Railroad and Copper Creek stream diversions: Railroad and Copper Creek ② have excess concentrations of metals above water quality standards established for the site as a result of contact with mill tailings and near-surface seeps. A portion of Railroad Creek, 1,143 m in length, was diverted northward into a new channel to provide sufficient access for construction of the reclamation components, to reduce the risk of erosion of the tailings, and to improve the river ecosystem. The Copper Creek channel, which divides TP-1 and TP-2, was modified and improved to reduce the risk of erosion of TP-1 and TP-2 and lined to reduce infiltration of clean surface water into the groundwater collection and treatment system.

Regrading and covering of East and West Waste Rock Piles: The East and West Waste Rock Piles ① have been regraded to configurations that are stable under steady state and seismic conditions and promote maximum run-off and reduce infiltration. This included reducing the slope from the angle of repose to a flatter 2H:1V slope. The top and side slopes of the waste rock piles have been covered with soil and will be covered with a rock mulch erosion control layer and will be re-vegetated.

Lower West Area (LWA) and lagoon reclamation: The LWA ③ was divided into east and west parcels. The eastern parcel consists of open areas and sparse forest, while the western parcel consists of the Lagoon area and denser forest. The Lagoon is an impoundment approximately 0.4 hectares in size that was originally constructed during the mine operation to serve as a settling basin for mine water from the 1500 Level Portal. Impacted soils in this area were capped and managed in place.

Maintenance yard reclamation: Soils in this one 0.4 hectare area ③ contain elevated concentrations of metals and total petroleum hydrocarbons in the form of gasoline, diesel fuel, and motor oil. Soils exceeding agency established clean-up standards in the Maintenance Yard area will either be capped and managed in place or excavated and consolidated into the tailings piles. The extent of the cap or soil removal required will be evaluated based on additional soil characterisation.

Former mill building demolition: The former Mill Building ④ was demolished in 2014 and was buried in situ to eliminate the safety risk associated with the dilapidated structure.

Remediation of surface water retention area soils: This area is located at the west end of the site and was formerly used as a water detention pond where fines in water from the mine ventilator tunnel (1100 Level) settled out and the water discharged via a decant structure. The deposited fines in this limited area have elevated concentrations of metals. Soils above agency established clean-up levels in this area will be remediated by capping and managed in place.

Groundwater containment, collection, and treatment: Groundwater beneath the tailings piles and along the edges of Railroad Creek exceeds regulatory levels for drinking water for aluminium, cadmium, copper, iron, lead and zinc. Groundwater adjacent to Railroad Creek exceeds some surface water quality standards. Exceedances of drinking water standards have not been observed in groundwater downgradient of TP-3. The concentrations of these metals and the groundwater flow rate into Railroad Creek vary seasonally along the length of the three tailings piles, with greater flow observed in the spring as a result of snow melt. A fully penetrating groundwater containment barrier wall ⑤, 1,430 m in length and with depths ranging from 7 to 28 m to the east, and collection system were constructed around TP-1, LWA, and the portion of TP-2, where Railroad Creek is a gaining stream, is to intercept impacted groundwater that would otherwise enter Railroad Creek and the lower portion of Copper Creek. Collected groundwater will be conveyed to a low energy mine water treatment facility ⑥, with 5,070 litres per minute treatment capacity, employing high density sludge and lime treatment processes. Sludge from the water treatment system will be disposed of on a constructed sludge filter cake disposal facility on top of tailings pile TP-1.

Portal bulkhead installation and hydraulic control: Concrete bulkheads ⑦ were constructed in 2014 to control discharge from The Main (1500 Level) Portal and the Ventilator (1100 Level) Tunnel. Air restricting adit plugs⑧ were placed in the upper mine ventilation to minimise air flow through the mine, thus reducing the rate of oxidation of sulfidic materials and attenuating contaminant concentrations in the portal discharge. The Main Portal bulkhead was equipped with a valved discharge pipe to allow controlled flow from the mine. The bulkheads enable the mine workings to function as a hydraulic equalisation reservoir by allowing water to build up behind the bulkheads in the spring and maintain a more consistent flow from the portal to the treatment system.

Surface water control and diversion: Surface water in Railroad Creek has been impacted by groundwater discharge from the Main Portal, seeps, and contact with tailings. However, surface water quality at the site does not exceed state and federal drinking water criteria. At a few sampling locations adjacent to, and downstream of the site, state and federal regulatory levels intended to protect aquatic life for aluminium, cadmium, copper, iron, lead, and zinc have been exceeded. Surface water will be remediated by preventing the erosion of tailings and subsequent discharge into surface water, and by controlling the discharge of contaminated seeps. Stormwater interception channels ⑨ upgradient from TP-1, TP-2, and TP-3 and the East and West Waste Rock Piles will be constructed to divert and control surface water run-on.

Sediment control: Iron precipitates have formed in Railroad Creek ② as a result of the release of ferric sulphate and other constituents from the tailings piles and adjacent seeps. Observed effects include ferricrete (stream channel gravels cemented with an iron oxide precipitate) and iron flocculent, which fills interstitial pore space in the sediment and coats gravel, cobbles, and boulders in the stream channel. Relocation of Railroad Creek has diverted stream flow away from most areas impacted by ferricrete formation within the streambed. Some ferricrete was excavated from the streambed along certain reaches adjacent to TP-2 as part of the Railroad Creek stream diversion.

Institutional controls and reclamation performance monitoring: Institutional controls will be implemented to notify the public of contaminated areas that will be left on site, and prevent humans from direct contact with hazardous substances by warning of the risk, and to protect the integrity of the reclamation by preventing changes in site use that would reduce the effectiveness of the reclamation. Long-term monitoring of the reclamation will be performed to assess reclamation performance, compliance with clean-up objectives and goals, and the overall protectiveness to the public and environment.

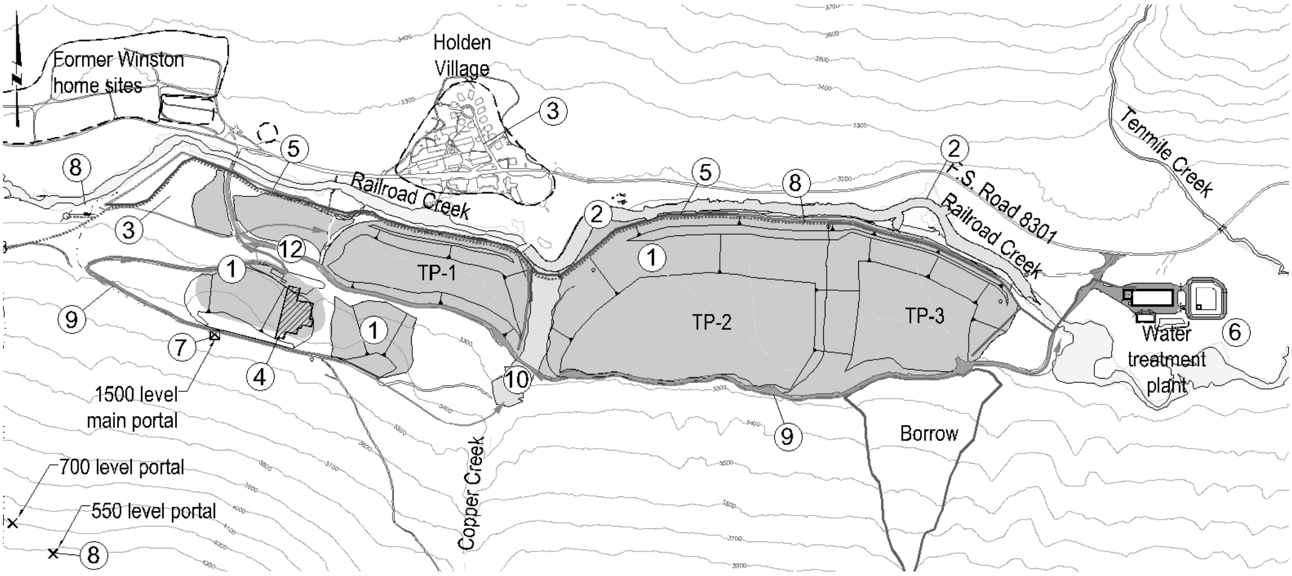

Figure 3 Primary reclamation components

2 Reclamation design methodology

The reclamation design was performed in accordance with the USEPA Superfund process, in accordance with the Site Record of Decision (USDA FS 2012). The reclamation strategy selected in the Record of Decision is to meet the overall closure objectives of preventing future water and soil contamination from past mining activities. The selected strategy was based on the assessment of different reclamation alternatives the Site performed under the USEPA Superfund process. The primary reclamation design components include: surface water management, grading and tailings stabilisation, cover, grading and covering of waste rock piles, creek restoration, barrier wall and groundwater collection, and water treatment. Other reclamation components included demolition of the mine mill structure, contaminated soil remediation, borrow area development, and infrastructure improvements (MWH 2014). The design methodology of the primary reclamation components are described in the following sections.

2.1 Surface water control

A network of approximately 6,310 linear meters of surface water channels were designed to control surface water run-on and run-off at the Site. The channels include both vegetation lined swales and riprap-lined trapezoidal-shaped channels to convey surface water run-off from the covered tailings piles and divert and control surface water run-on upgradient from the Tailings and Waste Rock Piles, respectively. The riprap-lined trapezoidal channels are between 1.2 and 2.4 m wide with 2H:1V side slopes and range in gradients from 0.5 to 13 per cent.

The design storm event for the channels included a review of maximum 24-hour precipitation events. The majority of maximum 24-hour events occur from November to February, at a temperature at or below freezing more than 50 percent of the time. Therefore, the design storm event for the channel design considered a rain-on-melting snow event that would occur during the spring months of the year. Rain-on-snow adds significant thermal energy to the snowpack and increases the run-off. An equivalent

150 mm amount of precipitation was estimated from snow melt for a 24-hour period using the Energy Budget Method's partially forested rain-on-snow equation (USACE 1998).

The design flows for the channel design are based on the combination of the flows produced by the 100-year, 24-hour rainfall event over the entire drainage areas, and the peak flows obtained from snow melt run-off using the Energy Budget Method. The Natural Resources Conservation Service (NRCS) method, formerly the Soil Conservation Service (SCS) within the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) program was used to compute run-off from rainfall. The design flows for the channels ranges from 0.03 to 4.8 m³ per second.

2.2 Grading and tailings piles stabilisation

A primary component of the reclamation was to address the possibility that the three tailings piles at the Site may become unstable under seismic conditions and release mine tailings into Railroad Creek and Copper Creek.

The Howe Sound original tailings storage facility design and construction consisted of realigning Railroad Creek and building a starter dam along the perimeter of the planned tailings pile footprint. Upright concrete risers were constructed at strategic locations with drainage pipe lines connecting the risers with a water spillage point outside the starter dam. Slurry pipelines were placed along the perimeter of the pile to distribute the tailings from the mill's floatation process. Tailings sands and slimes were delivered to the tailings pile areas (Zanadvoroff 1946).

Due to the limited space in the valley between the steep mountain slope and Railroad Creek, the mine identified the need for building up the tailings embankment slopes rapidly using a single and double diking method resulting in exterior slopes as steep as 0.8:1. Raises were mainly completed in the summer to avoid freeze/thaw sloughing effects. Railroad Creek was realigned four times between 1937 and 1948 to provide space for the additional tailings and to repair the base of the tailings piles due to erosion caused by high creek flows.

The tailings piles overlie the stream alluvium and glacial materials overlying bedrock within the valley bottom and lower valley walls of the Railroad Creek drainage. The alluvium ranges from 12 m to over 30 m in depth and consists of silty and sandy gravel to relatively clean gravel and boulders containing little to no fine-grained or silty material. Although historical records suggested that duff and overbank deposits were removed prior to constructing the starter dam, this could not be confirmed with certainty and some geotechnical borings revealed the presence of overbank material. Material testing of the overbank material combined with geotechnical analyses, including FLAC® modelling, of both the existing tailings slopes and the north facing regraded tailings slopes, suggested the saturated overbank and tailings material at the base of the tailings piles would result in unacceptable Factors of Safety under the maximum design earthquake event. The Factors of Safety were calculated to be less than the minimum required values under post-earthquake conditions for TP-2 and TP-3, as well as unacceptable deformations due to seismic loading conditions. An additional site constraint was the limited physical distance available between Railroad Creek and the tailings pile toe, so installing a toe buttress was not feasible. To improve the stability for TP-2 and TP-3 under seismic and post-earthquake loading conditions, a unique design approach was employed. The tailings pile embankments were strengthened using jet grout columns to improve the material characteristics of the saturated tailings layers and overbank material at the base of the tailings pile. This innovative approach is further described in Section 3.2.

The bulk of the grading included excavation for the realigned reach of Railroad Creek and flattening the slopes of the tailings and waste rock piles for stability and cover placement. Excess tailings and other materials were hauled and placed in a surplus materials consolidation area on top of TP-3 to balance the cut-and-fill quantities. Regrading the tailings pile slopes included an intermediate bench approximately one third up the slope for stability, and to provide access for equipment needed to jet grout the overbank/saturated tailings zone located between the bottom of the tailings pile and existing alluvium. The regraded slope below and above the immediate bench was 2H:1V and 3H:1V, respectively. The 2H:1V slope lengths were relatively short having an average length of 17 m. The 3H:1V slope lengths varied from 24 to 90 m and included a small bench midway on the slope. The reclaimed surface will be contoured to promote positive drainage as part of the overall surface water and sediment control system. Figure 4 shows a typical cross-section of the regraded tailings.

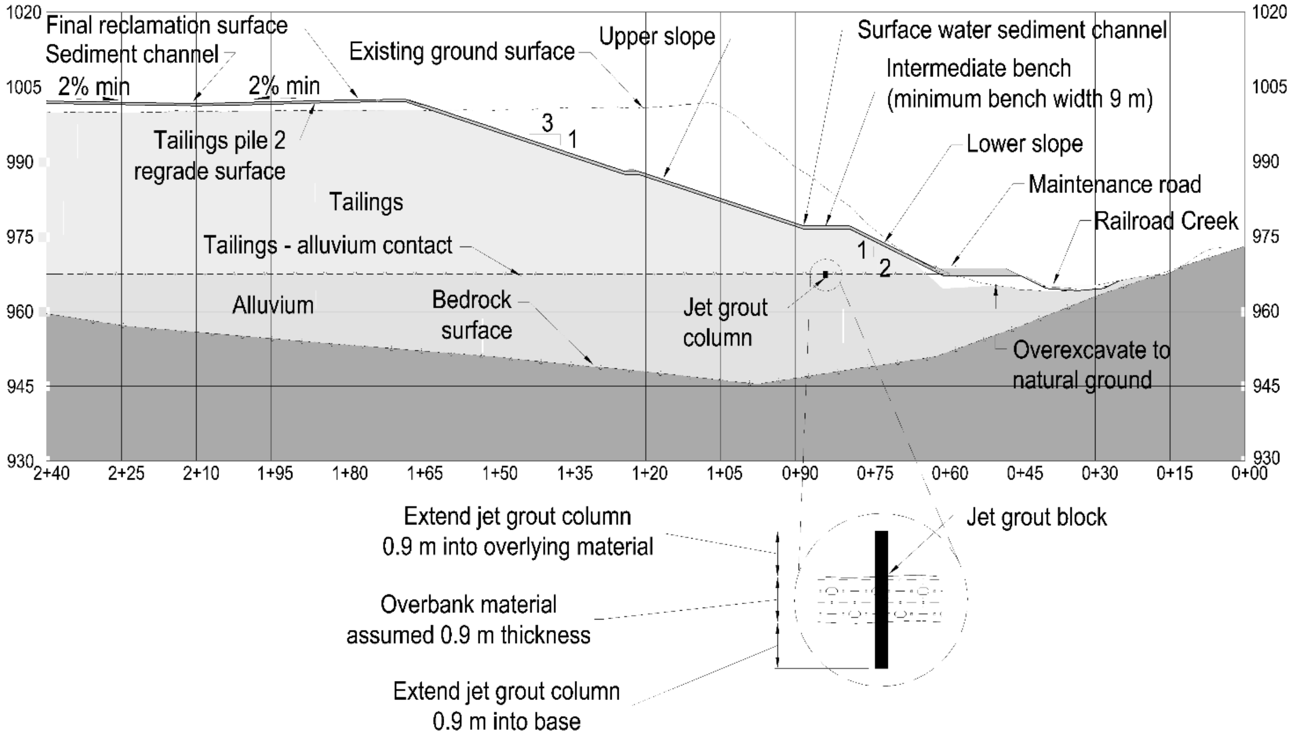

Figure 4 Regraded tailings pile typical cross-section

The Mill Building and surrounding structures were demolished and consolidated within the former Mill Building footprint. Material from the West Waste Rock Pile was blended with debris and used as fill to achieve a 2H:1V slope with an average length of 55 m. A typical cross-section is shown on Figure 5. Waste rock was also used for constructing the embankment for the mine water treatment plant sludge filter cake management facility located on TP-1.

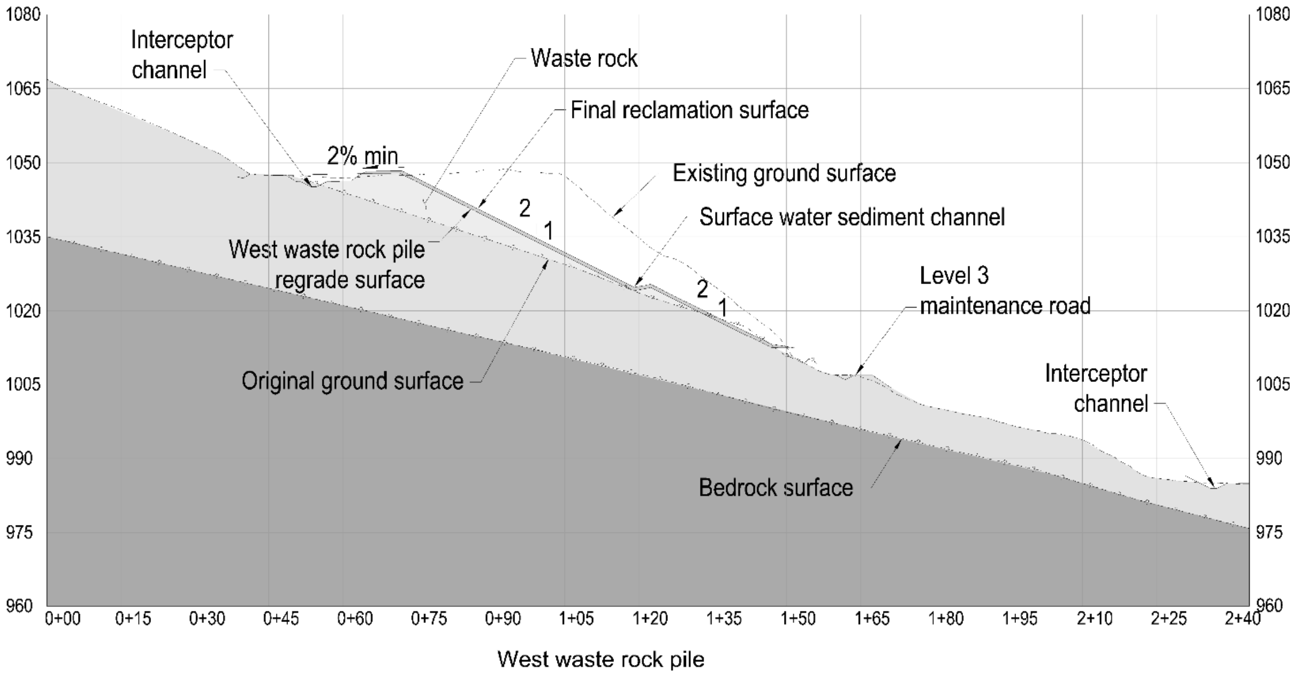

Figure 5 Regraded waste rock pile typical section

2.3 Multi-purpose cover

Minimising further loss of and replacing our world's forests have become a global environmental effort. The use of trees is included in the cover design for the tailings piles and waste rock areas to support conifers which are ubiquitous in the forest surrounding the site. The cover will also provide the traditional engineering function to protect the underlying tailings and waste rock from water and wind erosion, be maintainable, and, to the extent practical, be self-sustaining. The surface layer will also serve other purposes, such as promoting evapotranspiration, satisfying project aesthetics, and enhancing ecological objectives by providing a growth medium for vegetation.

Additionally, the cover design included an ecological risk assessment to demonstrate that a minimum 457 mm thick cover would be protective of mammalian and avian receptors, plant, and invertebrate receptor groups. The risk assessment included determining exposure pathways, the physical and chemical nature of the tailings and waste rock, and a toxicological assessment.

The final cover will consist of a growth medium ranging from 457 to 762 mm thick of soil with rock smaller than 102 mm diameter. The cover soil will be excavated from an onsite colluvium borrow. Slopes that are steeper than 3H:1V will include a 300 mm thick layer of rock mulch consisting of 76.2 mm D_{50} riprap for erosion protection.

2.4 Creek realignment and restoration

Approximately 1,143 m of Railroad Creek has been reconstructed to improve aquatic habitat and ensure long-term hydraulic stability of the tailings piles. The north bank simulates a semi-natural stream bank providing limited and controlled particle recruitment, as well as 1.5 m diameter boulders for aquatic habitat. Large woody debris was placed at various locations to mimic conditions in upstream reference stream reaches. Figure 6 shows the new alignment and reconstructed Railroad Creek. The south bank of Railroad Creek was armoured with riprap to prevent erosion of tailings by run-off and surface water flows in Railroad Creek (Figure 7).

Figure 6 Photograph of restored Railroad Creek looking west up valley and regraded tailings

Figure 7 Photograph looking south across Railroad Creek at the south bank riprap and regraded tailings pile

A flow of 130 m³ per second was determined as the maximum design flow event corresponding to a probability of 1:1,000 of being exceeded. This would be a large design flood event that would have a low probability of being exceeded over the long term. Quantifying the peak design flow rate using typical methods, e.g. USGS regional regression equations, would provide an overconservative flow. Consequently, a unique method was developed to estimate the peak design flow using a two station comparison approach. The two station comparison involves comparing data from a shorter term gauging station downstream of the site (Railroad Creek at Lucerne), to a longer term gauging station in a nearby river drainage (Stehekin River at Stehekin). The results of this correlation were used to extend the observed flow record of the site with the shorter record. Once the extended data setwas obtained, it was subject to LPIII analysis to determine peak flows for the site with the shorter record (Railroad Creek at Lucerne). The peak flows were then transposed to the required locations in Railroad Creek using a drainage area ratio method (Cline et al. 2012).

2.5 Barrier wall and groundwater collection system

To address impacted groundwater at the Site, the remedial action included installation of a low permeability barrier wall between Railroad Creek and the Lower West Area and the tailings piles. Space limitations between Railroad Creek and the tailings piles required the construction of a working platform for excavation and placement of the slag-cement-bentonite (SCB) slurry. The barrier wall is approximately 1,430 m long with a 69 m long segment (wing wall) on the east end of TP-1. The barrier wall extends from the west end of the Lower West Area to the approximate midpoint of TP-2, where Railroad Creek becomes a losing stream. The final alignment was adjusted to avoid large and older cedar trees while preserving stream bank riparian habitat, and allowing space for construction equipment. The barrier wall has a nominal width of 0.9 m and an average depth of 16.5 m below the existing regraded surface (e.g. top of the barrier wall working platform) with minimum and maximum depth of 7 and 28 m, respectively. The barrier wall extends vertically to the top of the glacial till, and/or bedrock. The mix design incorporated groundwater modelling requirements resulting in a 5×10^{-7} cm/sec permeability for the constructed hydraulic barrier. The barrier wall was built using a SCB slurry trench construction technique. SCB barrier walls are a specific type of cement-bentonite barrier wall that incorporates slag-cement into the slurry mix. The addition of slag cement results in lower hydraulic conductivity and superior resistance to sulphate and other chemical attacks than could otherwise be achieved with a standard Portland-cement-bentonite barrier wall mix.

A groundwater collection trench (French drain), located adjacent and parallel to the barrier wall, was constructed to collect impacted groundwater and convey it to the mine water treatment plant. The collection trench consists of a drain-rock gravel envelope with perforated collection piping. The groundwater collection trench is approximately 0.9 m wide and ranges in depth between 3.0 and 6.10 m. Figure 8 illustrates a section of the groundwater collection, barrier wall, jet grout and regraded tailings slope.

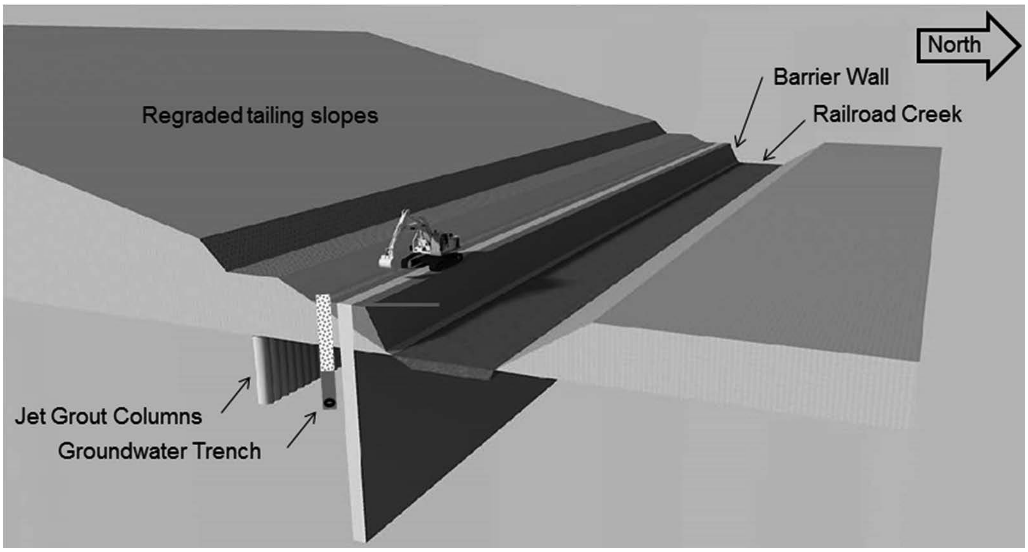

Figure 8 Barrier wall and groundwater collection trench

2.6 Mine water treatment

The low energy mine water treatment plant (WTP) is located on the east end of the site, down gradient of TP-3 and on the north side of Railroad Creek. The WTP will receive mine water from the 1500 Level Portal, seeps and groundwater collected along the barrier wall system. Collected water will be conveyed by gravity to the WTP where it will be treated for acidity and metals, then discharged by gravity to Railroad Creek. The treatment process employs high density sludge and chemical precipitation processes that utilise hydrated lime as an alkalinity source to neutralise acidity and induce precipitation of metal oxyhydroxides. A sulphide reagent is also added as a polishing step to further reduce dissolved metals concentration. A final effluent filtration step provides additional reduction of suspended particulate metals concentrations. Precipitant dewatering is accomplished with plate and frame filter presses. Sludge management and storage facilities will be included at the WTP, with final disposal of the sludge planned on top of Tailings Pile 1. The anticipated flowrate of collected groundwater is between 2,820 and 5,070 litres/minute. With minor modifications, the treatment plant has a contingency treatment capacity of 8,330 litres/minute. Figure 9 illustrates the layout of the mine water treatment plant.

Figure 9 Mine water treatment plant rendering

3 Unique design components

Unique reclamation design methods included applying conventional jet grouting methods to stabilise the regraded tailings impoundment embankment, design considerations for a gravity groundwater collection system, and developing low energy methods to reduce power requirements for water treatment.

3.1 Tailings embankment slope stability using jet grouting

Jet grouting is a common technical method used to improve soil strength when structures are built on soft soils (Wang et al. 2013). It consists of injecting fluids at a high velocity through a small-diameter nozzle to erode the soil and mix it with injected grout to form a soil-cement column. Cases of using jet grout columns to stabilise dam embankments have also been used, but to a lesser extent. This unique application required a combination of engineering analysis, investigation, and field trial through a robust quality control programme during construction.

Blocks of jet grouted cement columns, e.g. soilcrete, were installed to intercept the failure plane within the potentially liquefiable zone (saturated tailings and overbank material). To accurately define the vertical limits of the saturated tailings-overbank zone, a pre-jet grout investigation was performed that included cone penetration testing (CPT) and borings with standard penetration testing (SPT). Prior to production work, a test programme was also conducted to verify that the proposed jet grouting parameters could effectively achieve the design requirements, including: column geometry, soilcrete strengths, and soilcrete consistency. The field test programme was also used to optimise the various parameters including type of jet grouting (single, double or triple), grout mix composition, fluid(s) flows and pressures, rotational speed, retraction rate, and number and size of nozzles.

The columns were anchored into non-liquefiable materials above and below the potentially liquefiable overbank and saturated tailings layer. A soilcrete design strength of approximately 2.3 MPA and about 36 per cent coverage of the improvement zone was considered to be adequate (based on the stability evaluations) to address the shear strength improvement needs. The design also allowed space for internal drainage between the blocks of columns. The blocks of jet grouted columns varied between a 2 by 3, 2 by 4, and 2 by 5 (number of columns wide by number of columns deep perpendicular to the axis). The block of columns were spaced at 1.4 m centre-to-centre, in both directions, resulting in a secant-type overlap of 0.15 m between adjacent columns. A typical 2 by 3 column arrangement on the regraded intermediate tailings bench is shown on Figure 10.

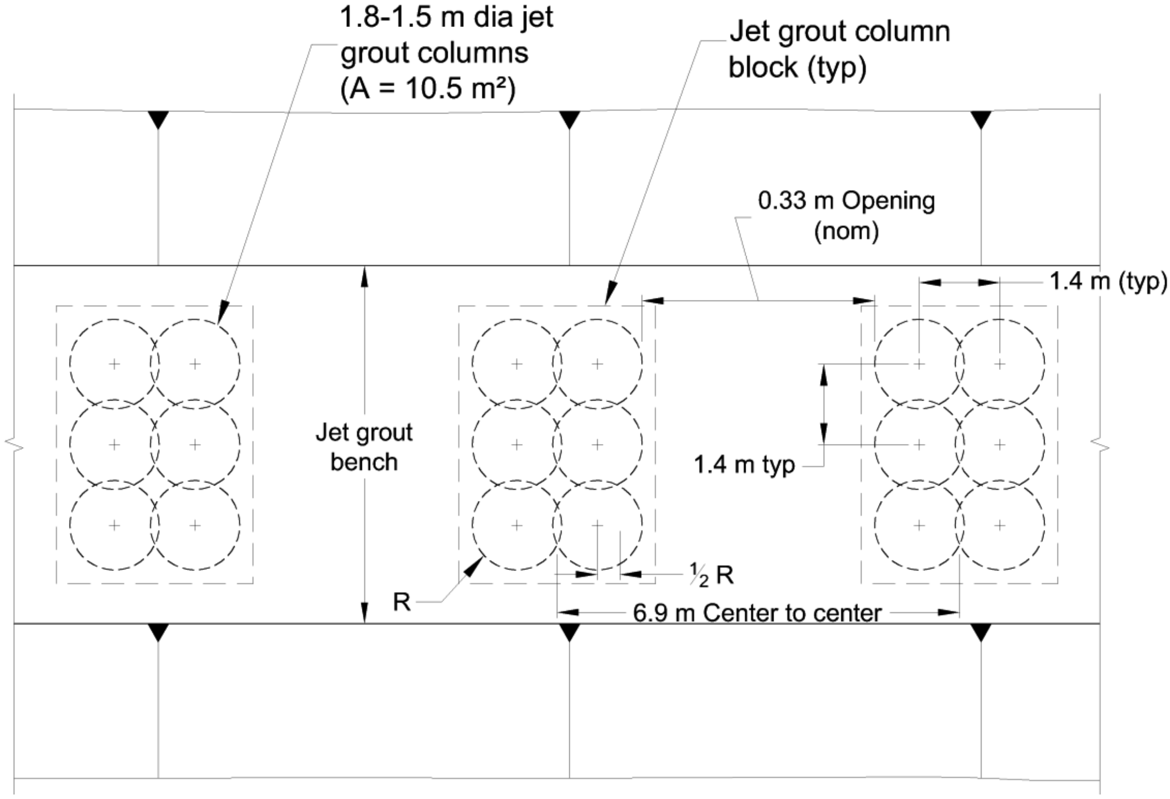

Figure 10 Typical jet grout block configuration plan

The jet grout column blocks were evaluated for sliding, overturning, and bearing capacity failure modes over the updated range of anticipated block heights. The flexural strength of the blocks was also evaluated to check the Factor of Safety against rupture. The analysis used the results of a stability analysis performed to estimate forces acting on the blocks for critical cross-sections where the thickest layers of potentially liquefiable material were identified.

The jet grouting columns were installed a minimum of 0.9 m above the saturated materials to a minimum of 0.9 m below CPT refusal so that they are anchored into non-liquefiable materials above and below the potentially liquefiable overbank and saturated tailings layer. The actual individual column heights within each block and the block geometries were adjusted, as needed, based on the alluvial contact elevations encountered in the field during jet grouting.

3.1.1 Pre jet grout investigation

The vertical extent of the potentially liquefiable zone was determined using a combination of 157 CPT soundings and 26 soil borings that were drilled in advance of jet grouting. The pre jet grout investigation had to be performed during the construction phase after the tailings slope were laid back to create a working bench so that the drilling equipment could access the area directly above the jet grout improvement zone (Figure 11).

Figure 11 CPT rig on working bench in advance of jet grouting. Regraded tailings pile slope shown on left side of photo

As expected, most of the tailings encountered consisted of sand to silty sand material, with occasional zones of finer grained material with lower tip resistance. Near the contact with the underlying alluvium, material with lower tip resistance and/or finer grained material was encountered, often associated with higher dynamic pore water pressures consisting of saturated tailings and/or overbank deposits. Overbank material was sampled in a few of the boring locations. It consisted of wet, dark grey fine grained sand and silt and decomposing organic material.

CPT information was used to identify the alluvium contact, groundwater levels, and liquefiable materials that the columns are required to intercept. Liquefaction triggering calculations were performed using methods developed by Idriss and Boulanger (2008) and by Youd and Idriss (2001), using the CPT data. The Factor of Safety for the tailings material was defined as the average value of these two methods at each depth for each CPT. If the Factor of Safety against liquefaction is less than 1.0 across a minimum 305 mm depth, the material was considered as liquefiable. Additionally, if there is a layer of non-liquefiable material (as identified by the analysis of the CPT data) of less than 30.5 cm in thickness in between identified liquefiable layers, then that entire zone was considered to be liquefiable. Approximately 60 per cent of the CPTs encountered liquefiable material.

Prior to production grouting, a jet grout field trial was performed at the Site to evaluate the ability of the proposed jet grouting methods and parameters to achieve the design soilcrete strength and column geometry. The jet grout trial was performed on a bench excavated along the eastern edge of TP-3 and exhumed for examination (Figure 12). This location allowed for exhumation and observation of the completed jet grout soilcrete blocks. The exhumation showed that the jet grouting was successful in creating a soilcrete column that would meet the project requirements.

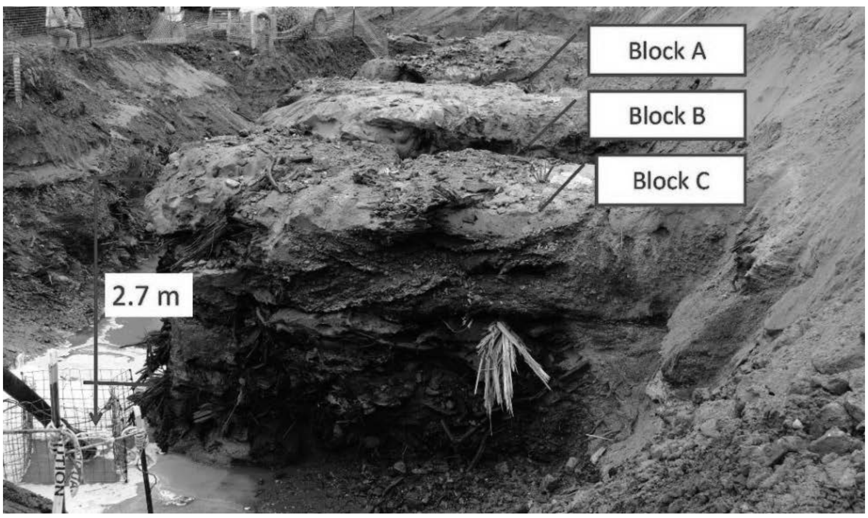

Figure 12 Exhumed trial jet grout columns

3.2 Groundwater collection system — gravity design considerations

The hydrologic system at the Site changes considerably between the late spring and early summer. From late May into early July, snowmelt causes high stream flows and elevated groundwater levels compared to conditions at other times during the year. The aquifer recharge is generally from 51 to 229 mm of water per year, or approximately 5 to 21% of the annual precipitation. There is rapid recharge in the spring due to snowmelt infiltrating along the mountain front and recharging the alluvial aquifer in the colluvium deposits that coincide with the debris/avalanche chutes. Mountain-front recharge from snowmelt in the spring is the main component to aquifer recharge. Recharge caused by infiltration of precipitation is a small component of the total inflow to the aquifer during the low flow times of the year. These variable hydrologic conditions provided a challenge for the designers in determining the collection trench depth and design flow rates to use for sizing the groundwater collection piping and other gravity powered hydraulic structures including the mine water treatment plant.

The first step in the design process was development of a groundwater model for the site. For the Holden Mine, the model was constructed in MODFLOW. MODFLOW is a three-dimensional finite-difference numerical code that can simulate steady-state groundwater flow in detail over a large area. Model development focused on the reclamation area using a telescoped model to allow smaller grid cells with dimensions of 3.1 by 3.1 m. The telescoped model was divided vertically into five layers to simulate the tailings, glacial till, colluvium and alluvium, glacial till and bedrock.

The groundwater model was used to establish the optimum configuration of the barrier wall. Alternate alignments and depths (fully- versus partially-penetrating) and lining Copper Creek were evaluated to determine the best containment and most effective capture of impacted groundwater. The most effective configuration consisted of the fully-penetrating barrier wall and lining of Copper Creek in the vicinity of the tailings piles. A partial penetrating barrier wall provided containment but allowed a significant volume of clean underflow from Railroad Creek into the collection trench. Lining Copper Creek with a low permeability geosynthetic clay liner (GCL) reduced the flow of clean Copper Creek water from entering the collection system. An eastern wing wall was added that wraps back south along the eastern end of TP-1.

There is a potential for secondary precipitates to form within the pipeline such as gypsum, as well as various metal (Mn, Al, Cu, and Fe) oxyhydroxides and hydroxysulphates. These secondary precipitates can contribute to component scaling within the groundwater collection system and were addressed by minimising the introduction of atmospheric oxygen to the collection system and limiting comingling of flows from various areas and sources. In recognition of the potential for secondary participates to contribute to scaling, a unique system of 24 water traps and 19 cleanouts were constructed to provide a robust system for cleaning and maintaining the groundwater collection system.

The water traps consist of a vault where there is a break in the collection trench pipe with the downgradient collection trench pipe higher than the upgradient pipe. This variance, approximately 0.8 m, provides a water trap by controlling the water elevation in the trench such that it maintains the pipe and the surrounding gravel envelope submerged during periods of low groundwater levels, thus restricting repeated oxygenation from cyclical groundwater levels. A low permeability plug is installed on the downgradient side of the water trap to aid in keeping the upgradient section of the trench saturated in low flow conditions. Figure 13 shows the water trap design.

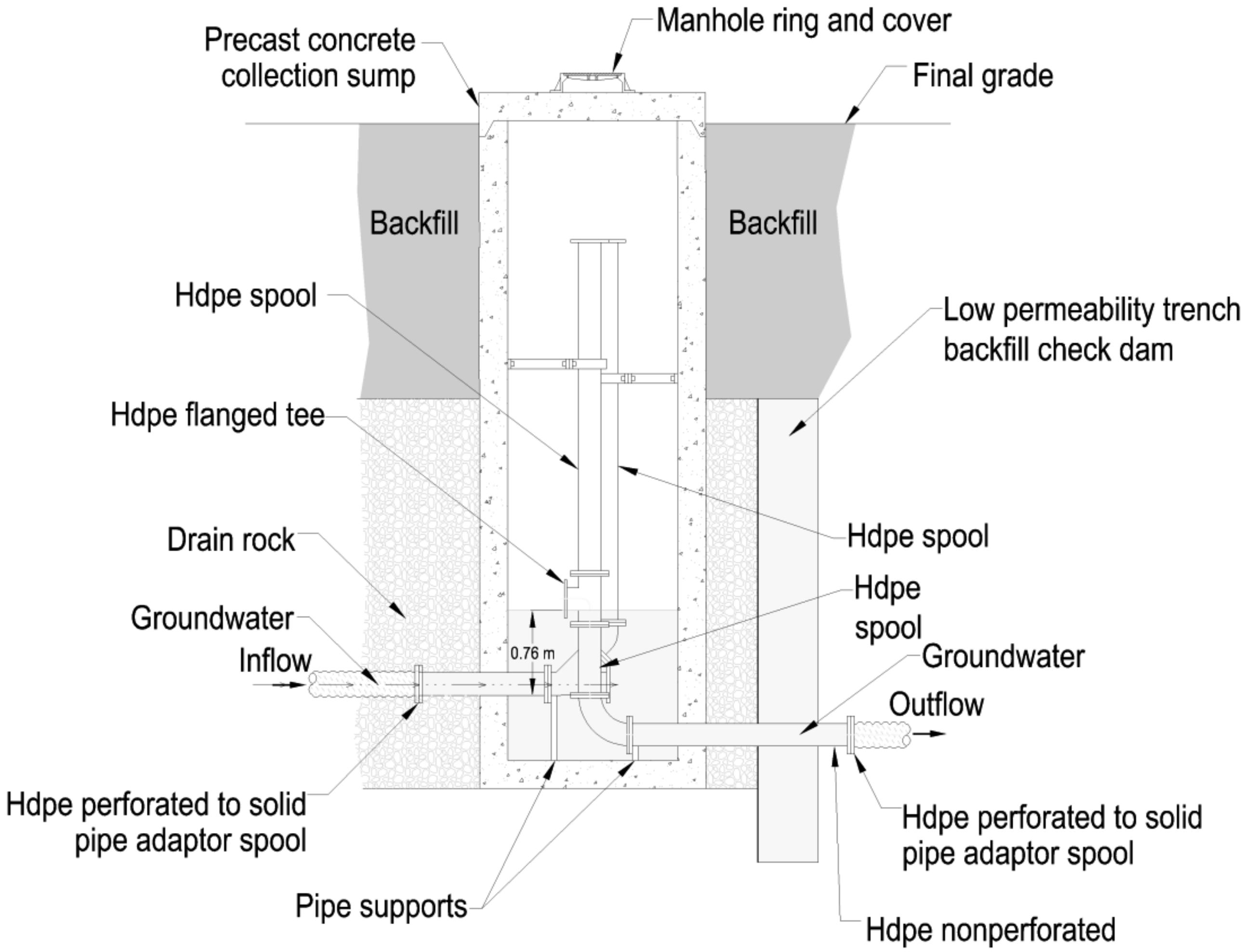

Figure 13 Groundwater collection trench water trap

3.3 Mine water treatment — low energy design methods

Minimising the power requirements is a common goal for most water treatment plants to reduce operating cost, carbon footprint and improve sustainability. Since there is no power available at Holden, power is provided from onsite 480V diesel generators sized to handle the daily operating loads of the plant and a contingency. Reducing the power demands was a critical design criterion for the treatment plant and was accomplished by incorporating power reducing concepts into the design. These include:

- Developing a gravity powered treatment system.
- Using hydraulic head from the mine portal bulkhead to power the lime feed system.
- Using variable frequency drive motors.
- Low energy building systems.

Collected water will be conveyed by gravity to the WTP where it will be treated for acidity and metals, then discharged by gravity to Railroad Creek. To achieve the low-energy requirement, the plant hydraulics are designed to allow gravity flow from the beginning of the process to the discharge at Railroad Creek. Dry lime will be slurried with the hydraulic energy from the 1500 Level Main Portal water using a 51 mm eductor pump having a minimum suction capacity of 91 litres/minute to slurry up to 1.8 kg per minute of hydrated lime. The 1500 Level Main Portal water pipeline will convey portal drainage collected behind the bulkhead to the mine water treatment plant. The 1500 Main Portal is approximately 61 m higher in elevation than the mine water treatment plant, providing the hydraulic head necessary to operate the lime eductor pump reducing power demand. Variable speed motors allow efficient use of power. The pumps are on variable frequency drives (VFD) to facilitate operational flexibility and reduce power consumption.

Lighting within the building will be via Light-Emitting Diode (LED) lights to conserve energy. The lighting throughout the building will be controlled by motion sensors and photo sensors with manual overrides. Each of the three rooms (Process Room, Filter Press Room and Sludge Storage Room), within the main building, will be controlled as three separate zones, meaning that when unoccupied these rooms will be unlit to conserve power draw. Heating ventilation and air conditioning equipment is specified to perform at or above code required minimum efficiency levels. All ductwork and refrigerant piping is properly insulated, to prevent heat loss. In order to conserve power and match ventilation with heat load, 2-speed fans are used or multi-fans are used and cycled on and off.

The water treatment plant will require an average load of 126 kW. This load represents the electrical demand incorporating a utilisation rate for equipment that is expected to operate intermittently.

4 Conclusion — lessons learned for advancing mine closure

The first in a series of technical papers, this paper provides the mine closure community with an overview of some of the innovative design and construction techniques that have been applied at the Holden Mine with the goal of further advancing the state-of-practice for mine closure and remediation at other sites. The Holden Mine reclamation required development of an integrated system of mine closure components including infrastructure improvements, surface water control and sediment management, grading and tailings stabilisation, embankment slope stability improvements, grading and covering of waste rock piles, mill demolition, creek realignment and restoration, barrier wall installation and groundwater collection, mine water treatment, and a multi-purpose cover design. Integration of these mine closure components was critical to develop the reclamation design criteria. In addition, consideration and inclusion of site logistic issues also had to be incorporated into the design because of the site remoteness, lack of available power or roads to the mine, shortened construction seasons, and extreme climatic and terrain conditions. Finally, frequent and continuous stakeholder involvement, communication and collaboration were necessary to ensure the design considered all stakeholder interests.

Project successes and lessons learned included the following:

- The design of surface water channels, which encompass over 6,300 linear meters, required consideration of a rain-on-melting snow event as rain-on-snow adds significant thermal energy to the snowpack and increases the run-off.
- Post-earthquake stability modelling confirmed the three tailings piles could become unstable under seismic conditions and possibly release tailings into Railroad Creek and Copper Creek because of an underlying overbank deposit beneath the tailings piles.
- Detailed design revealed that inadequate space was available between Railroad Creek and the tailings piles for barrier wall construction necessitating realigning Railroad Creek to construct a working platform.
- Since space restrictions precluded the construction of a rock toe buttress along the tailings embankments for stabilisation, jet grouted columns using soilcrete were employed to strengthen the tailings pile embankments and improve the material characteristics of the saturated tailings layers and overbank material at the base of the tailings piles.
- Pre-design investigations and evaluations were instrumental to develop the design and specification packages; particularly for the pre-jet grouting drilling programme for tailings embankment stabilisation and for the barrier wall installation and construction.
- The introduction of atmospheric oxygen and the formation of precipitation can foul drain rock in a gravity groundwater collection trench. Water traps and low permeability plugs provide a means to keep the drain rock in the groundwater collection trench saturated to reduce the introduction of

atmospheric oxygen. Limiting the comingling of flow sources with different water chemistry also reduce the formation of precipitates.

- Power reducing design methods for mine water treatment plant included lime feed inductors powered by the hydraulic head of the portal drain, gravity for hydraulic flow through the plant instead of pumps, variable frequency drive motors, and low energy building systems.
- Effective project planning during the off-season proved to be extremely valuable for pre-design investigation development, site logistics, and construction sequencing.

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