Integrated Closure Planning for a High Altitude Pit Lake in the Peruvian Andes

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Abstract

A conceptual closure plan was developed for a high altitude copper mine in the Peruvian Andes where pit highwalls extended up to 450 m above equilibrium water level. These highwalls presented a surge wave risk due to regional seismic activity. A key aspect of the conceptual design was the novel use of a waste rock dump to provide surge wave protection to the communities located on the river below the mine site. By incorporating mine waste landforms in the valley downstream of the pit lake we sought to attenuate the risk of these flood events.

Keywords: Peru, Pit Lake, Mine Closure, Seismic Activity, Waves

Introduction

Mine pit lakes are a common feature of open cut mine closures that extend below the local groundwater levels (Castendyk and Eary 2009). With large water volumes which often contain waters degraded by contact with enriched geologies, pit lakes can represent a relevant risk at mine closure.

However, due to the relatively steep lake bottom profiles compared to natural lakes, shoreline stability may also be a substantial limitation to the rehabilitation and sustainable closure of pit lakes (Lund and McCullough 2011). Globally, metal mines tend to have steeper sided lakes and coal mines relatively shallower lakes (Schultze et al. 2016). This steepness may potentially influence upon highwall geotechnical stability, revegetation success, water quality and proposed end uses including wildlife habitat, aesthetics and recreation (McCullough et al. 2020).

Pit lakes can represent the highest environmental risk closure landform for many mines (Doupé and Lymbery 2005). Despite the issues relating to long-term pit lake closure planning and management, there is currently very little information available on pit lakeshore erosion, including potential erosion rates and extent (Vandenberg and McCullough 2017). Although water quality is typically the focus, recent work has highlighted pit lake wave action on sensitive surrounding receptors as a key knowledge gap to many closure plans proposing pit lakes as final landforms (McCullough et al. 2019).

Waves and shoreline erosion

The strength of pit wall materials may change during filling because of reduced normal stress on the materials near the pit walls or as a result of water flow along fractures or geologic structures. Rising lake water levels may then cause erosion of softer deposits, leading to undercutting and overhanging zones to form. These small pit slope failures are therefore not unusual during the pit filling process and may also occur once the final lake level has been established (Read and Stacey 2009).

The shoreline morphometry of a pit lake is determined by the original void shape and modified by any backfilling and shaping. The hydrodynamics of wind-forced waves are well understood and models are readily able to estimate wave characteristics for deep, open water and continuous shorelines (McCullough et al. 2019).

However, even decades-old pit lakes, frequently show very high rates of shoreline erosion (Vandenberg and McCullough 2017), often as sudden catastrophic highwall failures (Castendyk et al. 2020). Steep, eroding pit lake shorelines reduce end use opportunities and values (McCullough et al. 2018) and can present a relevant risk to health and safety of visitors and local communities (Ross and McCullough 2011). In particular, surge waves have been identified as a potential risk for some pit lakes with potential for large mass failures (landslides) of highwalls in pit lake surface waters (Gammons 2009).

Study site

The Project is located in the Peruvian Andes in the Province of Pallasca in the northern part of the country. Project area altitude ranges from 3,900 to 4,700 m above sea level (masl). The ore deposit is located in a glacial valley with steep valley walls (fig. 1). The top of the projected final pit nearly reaches the 4,600 m elevation above sea level (masl), while the bottom of the pit is at 3,800 masl. This results in a highwall on the north side of the pit that is nearly 800 m high and slightly less on the south side of the pit. The pit above 4,200 masl does not extend the full circumference of the pit. High elevation ore only occurs on the south side of the pit and is below 4,280 masl. Most of the material above 4,200 masl is limestone, none of which is ore grade.

Following dewatering ceasing, hydrogeological modelling indicates that a pit lake will form in the pit void. The open pit will infill predominantly with groundwater over approximately 15 years and then discharge into the valley below. It is expected that rainfall, infiltration and surface drains will maintain a largely stable pit lake water level.

On November 10th, 1946, an earthquake of M7.3 caused 1,400 deaths in the region and nearly all buildings were destroyed or heavily damaged in the Sihuas-Quiches-Conchucos strip (along an active fault close to the Project). Many landslides occurred; one buried the village of Acobamba and another dammed the Pelagatos River, around 10 km north of the Project site (USGS 2020). The downstream village was also flooded by obstruction of the local creek. Consequently, the planned pit lake remains a concern for the inhabitants.

Issues

Previous planning

A previous conceptual mine closure plan (CMCP) proposed a closure design for landforms of the project area. The open pit void was designed as a deep pit lake. A smaller lake in the valley immediately below it was proposed by damming the valley with a large waste rock dump (WRD). A further waste dump was located in the north of the project valley and a wet tailings storage facility (TSF) in the south below the valley WRD.

Following public dissemination of the CMCP, the following points were deemed issues specific to the pit lake that still needed to be resolved to obtain government approval (Hurst and Pacey 2004).

1. The ESIA (containing the CMCP) was initially rejected by the regulators without sufficient community stakeholder engagement and after receiving community feedback.
2. No risk assessment was performed.
3. The large open pit proposed at closure presented a largely unconsidered risk of a

Figure 1 *Site location geography.*

constructed lake upstream and near to the community.
4. There was no proposed rehabilitation and end use development identified for impacted areas.

The pit void presented a highwall fall risk to visitors and local community. The risk of seismic activity and rockfalls presented a risk of surge waves forming within the pit following pit wall collapse; discharging down the project valley. Based upon low likelihood but high consequence, this risk was assessed as moderate. Consequently, the previous operator's mine closure plan was rejected by nearby community stakeholders, primarily because it presented an unacceptable risk of surge waves.

Closure Conceptual Design

The closure plan's objectives aimed to meet both Peruvian mine closure regulatory requirements as well as the expectations of key stakeholders including the concerned villagers downstream of the mine. Following Peruvian mine closure requirements (República del Perú 2008) and international leading practice (e.g. ICMM 2008) the primary aim of the pit void closure concepts is to mitigate risk and to maximise benefit to local and regional communities and environments after mine closure. Given the interaction of the pit void with other closure landforms and the need for mine closure planning to be holistic across the project area and greater region, we also considered other landforms such as the Valley WRD in our design and assessment.

In order to provide a conceptual closure strategy to design, cost and further develop a development of the revised closure and rehabilitation plan was based on the following objectives:

- geotechnical stability of post-mining landforms and safety to the local communities accessing the site;
- geomorphic stability of the reclaimed landscape (i.e., minimize through near-natural rates of erosion and sediment transport);
- consultation with the mining company and other contractors designing the operational site layout to ensure compatibility and minimize earth movements for closure works; and
- provision of a post-mining land use values equal to, or better than, pre-mine land uses.

Backfill

Complete backfill is typically recommended to avoid pit lake water quality and high slope safety and stability problems (Puhalovich and Coghill 2011). However, placing fractured and unweathered rock in a pit void that has filled with water may cause groundwater pollution if the pit lake is a through-flow system (McCullough et al. 2013). Because mine waste contained skarn and porphyry, a plume of highly geochemically enriched groundwater may extend away from the lake system in the direction of groundwater flow. Consequently, pit void backfill was not considered good environmental practice as a surge wave engineering solution.

Pit lake

An holistic conceptual closure design will reduce pit lake risks to health and safety of villagers to acceptable levels as follows. A drainage channel will reduce lake volume from previous designs and also increase the lake freeboard, preventing and mitigating many surges (fig 2, top left). A 10 m high security berm will be constructed from waste rock to attenuate any potential flood waves in the event of a slope failure of the open pit. A 2 m high security berm will be constructed near the outlet to the project's valley. A safety berm will also be constructed around the open pit to prevent access of stock and people to any remaining highwalls. The security berm has been used in other regions of Perú (Letient et al. 2006) and will provide wave protection from small to medium-scale wave events. Beach areas will be constructed where practicable to provide safe entry for stock watering access and also lake edge habitat for wildlife likely including a rainbow trout fishery (*Onchyrynchus mykiss*) used by local communities. The beach areas will also reduce wave erosion potential along their gradient.

Valley WRD

The Valley WRD will be specifically engineered as a dyke to provide discharge during normal flow events and to control and retard high flow events such as may occur following a wall slump into the lake. The Valley WRD will be constructed asymmetrically along the south side of the valley, sloping to the north (fig 2, top right). Where practicable, bench width will be minimised and graded toward the valley floor to prevent water ingress through bench flats during precipitation and snowmelt events. Topsoil placement and revegetation with grasses will also provide a capture and release cover.

Rainfall data and valley stream flow data will be collected over the mine life to provide a good understanding of engineering requirements for the Valley WRD. The Valley WRD will also be specifically engineered as a dyke, with geotechnical and geochemical assessments of all construction materials specifically made to this purpose. It will be engineered to most probable flood and seismic event capacities.

Channel

The low rates of baseflow discharge from the pit lake will primarily be through the fractured rock waste base of the Valley WRD and through the karst system on which the Valley WRD is located. The channel will be constructed along the north side to carry pit lake discharge during flow events greater than baseflow but less than substantial flood events (fig 2, top right). This channel will be armoured with marble and limestone excavated predominantly in the unweathered initial overburden removal.

The channel will serve to reduce lake water level therefore reducing pit wall geologies exposed to direct water contact and wave action. This decreased water level also increases lake freeboard and reduced lake volume, providing further protection from surge waves.

Risk Assessment

A summary of inherent risks, risk management and consequent residual risks is shown below (tab. 1). Following the risk mitigation features incorporated in the revised design, residual risks are as follows:

1. surge waves. Based now upon very low likelihood and medium consequence, this risk is now low.

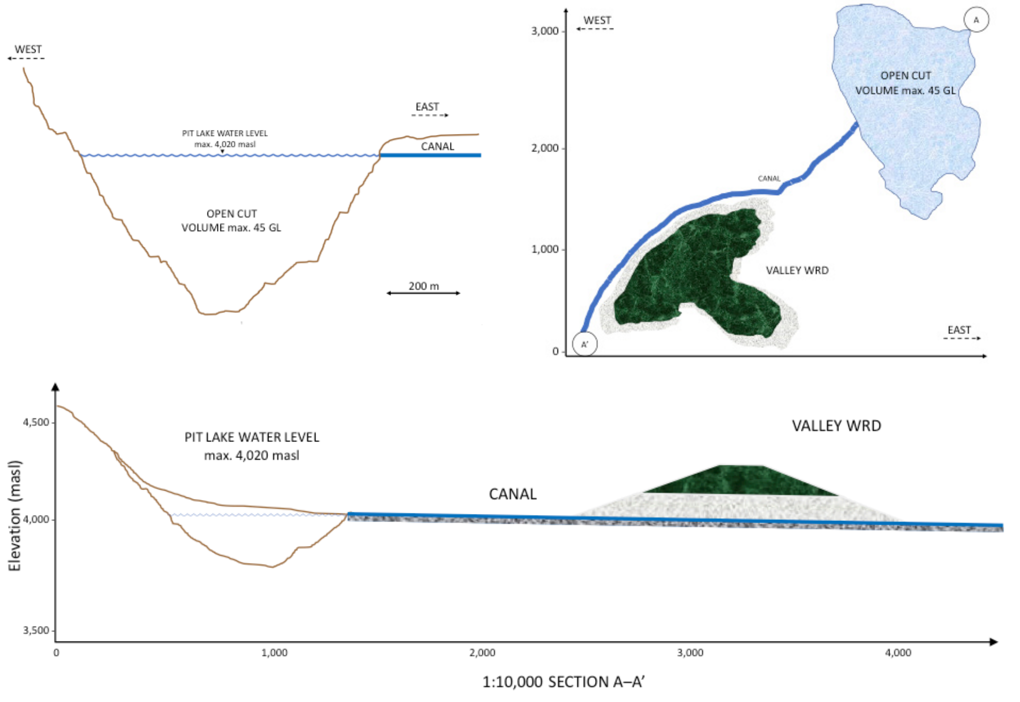

Figure 2 *Landform closure design.*

2. highwall falls. Based now upon low likelihood and medium consequence, this risk is now low.

Conclusions

Rather than a simple check box exercise, pit lake closure planning should be based upon risk assessments to potential receptors of wildlife, humans and other relevant end uses e.g. local community safety presented in this example. Further, pit lake closure planning should be undertaken with a holistic approach that considers the risk and interaction of other landforms upon each other. In this manner synergisms and efficiencies will often realise better pit lake, and overall, mine closure outcomes (Vandenberg and McCullough 2017).

The greatest risks associated with the case study's pit lake closure were found to be that of surge waves following seismic activity. An appropriate strategy to reduce these risks was developed by having a wet pit void of minimum water level and maximum freeboard and landscape engineering to prevent access and surge wave protection to reduce flood risk. The greatest reduction in wave risk would be achieved by engineering a Valley WRD with a diversion channel.

The updated CMCP was shared with the community technical advisors and stakeholders, receiving positive feedback and finally leading the approval of the environmental certification by the authorities. Therefore, integration of community concerns was another key design factor of this example.

Studies should now further evaluate the identified risks and proposed mitigation and management strategies over life-of-mine for development into a detailed closure strategy. Estimates of closure cost and of potential end use opportunity should also now be made.

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Table 1 *Risk assessment summary.*

Hazard	Inherent	Management	Residual
Surge wave	Low likelihood and high consequence **MODERATE RISK**	Security bund Valley WRD Channel	Very low likelihood and medium consequence **LOW RISK**
Highwall falls	Moderate likelihood and high consequence **HIGH RISK**	Safety berm	Low likelihood and medium consequence **LOW RISK**

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