Water Management in the Closure of Tailings Storage Facilities

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ABSTRACT

Tailings are the most visible remaining signs of mining activity, that together with mine waste rocks and open pit, are recognized as the "legacy" impacts of mining. In the past, the primary aim was to provide a well-engineered structure into which tailings can be deposited without a great deal of attention given to closure requirements or long term management of tailings storage facilities (TSF). Nowadays, the closure of TSF, must be planned at the beginning of the project so environmental, health and safety impacts do not remain in time after the closure. Not having a closure plan during the design stage may present serious economic consequences for the project, since closure costs without the planning at the end of mine life could threaten the project global economy. This implies that the closure concept must be included in the early phase of the TSF, to guarantee minor impacts in the future and ensure cost-effective closure activities considered in the global budget of the project.

This paper presents a guide to water management in the closure of TSF with focus on physical, hydrological and geochemical stability and its co-relation to improve closure activities for the long term waste and water management. Main impacts on water resources and TSF closure technologies are described like a methodology that needs to be engineered for closure during mine life by civil works and regular monitoring activities, so stability and environmental performance objectives can be achieved.

Successful TSF closure history cases are presented considering application in Chile and Peru, describing their design criteria, learned lessons, advantages/disadvantages, and technology performance under particular Andean region conditions.

Keywords: Contact/non-contact water management, TSF physical/hydrological/geochemical stability, seepage/infiltration control, covers, ARD mitigation

INTRODUCTION

Recently, there has been an increasing awareness for environmental and social sustainability of construction, operation and closure of mining projects. One of the main components that persist after closure is tailings storage facilities (TSFs). Whilst the engineering and geotechnical principles involved in the design of TSFs have been well developed in recent years, many attempts have been made, often on a trial and error basis, to ensure the long-term stability of TSF. Tailings are generally stored on the surface either within retaining structures (slurry or thickened tailings) or in the form of piles (paste or filtered tailings), but can also be stored underground in mined out voids (hydraulic fill or backfill tailings), or below water (lakes and sea) (Vick, 2001). In all cases TSFs host a residue that contain minerals, metallurgical reagents and water that can dissolve and transport contaminants to soil, groundwater and surface water. Also, site conditions may cause hydraulic erosion and soil liquefaction. For this reasons, water management of TSFs is an important issue to maintain physical, geochemical and hydrological stability after closure.

GEOCHEMICAL STABILITY ISSUES

Acid rock drainage (ARD) from mine waste is a worldwide environmental problem that can cause deterioration of downstream groundwater and surface water systems affecting aquatic biota. Weathering of sulphide minerals present in mine waste is responsible for generation of ARD. The quality of ARD is controlled by mineralogical and geochemical reactions in TSFs, and the outcome of these reactions is reflected in seepage waters surfacing through tailings dams, infiltration to soil and to groundwater. However, the design of tailings impoundment and tailings disposal technique ultimately determine whether sulphide minerals are exposed to weathering and whether mine drainage starts to form (Dold, 2014a).

Geochemical Considerations

Geochemical considerations for closure in TSFs depend on tailings disposal method. Most known disposal methods are surface, sub-aqueous and underground tailings disposal. Sub-aqueous (lake or submarine) tailings disposal has the advantage of eliminating air (oxygen) to minimize the oxidation of sulphides and prevent ARD with a low-cost closure and maintenance system. However, this method has been banned and restricted in several countries due to the high risk of environmental contamination. Historically, several cases of sub-aqueous tailings disposal has ended in final liberation of contaminants under reducing conditions, dispersion of chemicals from tailings and sediment contamination after decades of monitoring (Dold, 2014b). This has left impacts on aquatic biodiversity and risk of bioaccumulation of metals through food chains. The feasibility of sub-aquatic tailings disposal is dependent upon specific circumstances, extensive analyses of geochemical characteristics and its response under specific sub-aqueous conditions (Dold, 2014b). Monitoring of water quality, sediment quality and aquatic life is an important tool to control and evaluate sustainable closure.

Underground tailings disposal can prove viable for some of the tailings produced in mine life. In abandoned open pit mines, tailings material can be used to backfill the void, eliminating air (oxygen) and water contact with pit walls and water (groundwater, rainfall) decreasing closure costs associated with the tailings material at the same time as pit remediation. In underground mines tailings material can be used, after geochemical treatment and cement mixer, for structural purposes on stopes. In this case, monitoring of groundwater and superficial water downstream is an important tool to control and evaluate sustainable closure.

Surface tailings disposal is the most common method, mainly because it is preferable to store tailings on the surface where potential negative impacts can be managed. However, the main problem with surface deposition is that it is very difficult to achieve a sustainable closure solution for surface TSFs since ultimately all materials decompose, erode and are transported to the oceans in geological time scale (Szymanski and Davies, 2004). Also, there is a constant risk of ARD generation by the contact of sulphide tailings with water (groundwater, rainfall) and oxygen (air). In surface tailings disposal, sulphide oxidation with subsequent metal release may occur in the unsaturated border zones close to the embankments (borrow, rockfill or cycloned tailings sand dams) and at the tailings beach surface in active impoundments (Chambers, 2012). Metals released in sulphide oxidation can be retained by secondary precipitates that had formed as a result of oxidation. This mechanism prevents the downward transport of metals in the circum-neutral conditions. However, in acidic conditions, metals are no longer retained in the precipitate and rather dissolved in ARD (Tabra and Lange, 2014). Is relevant to mention that not all metals will precipitate in neutral condition and even neutral drainage may be potentially contaminant.

TSF Site selection - tailings characterization and ARD prediction

Baseline information (seismic, geological, geotechnical, meteorological, hydrological, hydrogeological, biological, soil/sediment quality, flora, fauna, social, and economical) of potential sites for tailings disposal and geochemical characterization of tailings material, are important aspects to consider for the selection of tailings disposal site and disposal method. Land and water uses of populations, flora and animals near and/or downstream tailings disposal site must be considered. Some of these aspects are summarized in the following table.

Table 1 Environmental Aspects for TSF Disposal and Closure Water Management Systems

Environmental Aspects		Tailings disposal	Closure Water Management System
Weather	Rainy (Tropical or Highlands)	Thickened Tailings/sub aquatic disposal	Diversion ditches, spillway, channels, grout curtain, cut off trench, underdrain, drainage system, collection pond, passive or active effluent treatment
	Dry (Desert)	Dewatered tailings/ in pit tailings disposal or co-disposal with waste rock	Diversion ditches, spillway, channels, drainage system, collection pond, passive or active effluent treatment
Geomorphology	Steep terrain	Conventional disposal	Diversion ditches, spillway, channels, grout curtain, cut off trench, underdrain, drainage system, collection pond, passive or active effluent treatment
	Flat terrain	Thickened tailings/Filtered Tailings/ In pit tailings disposal or co-disposal with waste rock	Diversion ditches, spillway, channels, drainage system, collection pond, passive or active effluent treatment
Seismicity	High	Dewatered tailings	Diversion ditches, spillway, channels, drainage system, collection pond, passive or active effluent treatment
		In pit tailings disposal / backfilling mine stopes	Pumping wells, collection ponds, passive or active effluent treatment
	Low	Co-disposal	Diversion ditches, spillway, channels, drainage

Environmental Aspects		Tailings disposal	Closure Water Management System
			system, collection pond, passive or active effluent treatment
		Conventional disposal	Diversion ditches, spillway, channels, grout curtain, cut off trench, underdrain, drainage system, collection pond, passive or active effluent treatment
Hydrology	Rivers, creeks (at the proposed site)	Conventional disposal	Diversion tunnels and coffer dams (derivation of rivers and creeks), diversion ditches, spillway, channels, grout curtain, cut off trench, underdrain, drainage system, collection pond, passive or active effluent treatment
	Lake, sea	sub aquatic disposal	Aquatic flora and fauna monitoring, submarine flow monitoring
Hydrogeology	Unconfined aquifer, discharge zones, geological faults	Thickened tailings/Filtered Tailings	Diversion ditches, spillway, channels, grout curtain, cut off trench, underdrain, drainage system, collection pond, passive or active effluent treatment
	Confined aquifer, no discharge zones	Conventional Tailings / Dewatered tailings	Diversion ditches, spillway, channels, drainage system, collection pond, passive or active effluent treatment

Prevention of ARD

Prevention is the key to avoid negative environmental impacts and costly mining mitigation. ARD prevention may consider at least three basic options: pyrite removal, oxygen exclusion and water control. Pyrite removal from tailings prior disposal is an effective measure to prevent ARD. The residue with high content of pyrite may then be disposed in an anoxic or confined environment. The second option consists to dispose tailings with acid generation potential in an anoxic environment avoiding sulfide reactions, metal leaching and the subsequent migration of weathering products that result from sulfide oxidation. In the closure phase of TSF, this can be achieved by the development of an effective and durable barrier to oxygen, such as water covers, dry covers and/or geosynthetic membranes. Two types of covers are used to isolate wastes and prevent ARD: dry and wet covers techniques.

Dry covers

The dry cover approach aims to reduce the oxygen flux into the tailings, thereby minimizing sulphide oxidation. The amount of acid water formed is also reduced by limiting the water percolation into the tailings. A dry cover usually consists of a combination of drainage layers and sealing clay, inert or non-reactive tailings, geotextile and organic material. Dewatered and reagent-less tailings material is placed on top of the liner to act as an inert protective layer. A gravel and impermeable layer or waste overburden is placed on top of the inert tailings. This cover can be applied in surface and underground tailings disposal. Dry covers behave as a “water stock-release” structure that enhance evapotranspiration and minimize infiltration. The cover thickness will determine its water storage capacity and will be defined as a function of the local rain pattern. About quantitative criteria of water storage and release in dry covers, research should be oriented in that direction, requiring detailed studies and focused on this topic.

The main drawback with the dry cover technique is that it has a relatively high cost (earthworks and soil processing activities) that is difficult to get right.

Wet covers

Water covers are considered to be one of the most effective methods for the mitigation of potentially acid generating tailings. The water cover in man-made lakes and in situ flooded basins is generally shallow (less than 2m) to minimize the size of dams constructed. To limit metal transfer to the water cover, protective layers of sand or organic material are sometimes placed over the tailings to act as a diffusion and mass-flow barrier. A potential problem that should be mitigated is wind-induced mixing and re-suspension. Underwater disposal in natural water bodies is preferred since provides a deep water cover. However, as already mentioned, this method has been banned and restricted in several countries due to the high risk of environmental contamination (Dold, 2014b). A limitation to wet covers may also be the physical stability of TSF, particularly in seismic environments, with risk of water overtopping.

Liners

The use of liners is significantly less common in tailings facilities for mining closure activities. Synthetic materials, such as high density polyethylene (HDPE) are often used with compacted clays to form a composite lining system to prevent polluted seepage through the facility foundation. Liners are commonly used to facilitate the permitting process. This practice has however largely been avoided on cost grounds. New geosynthetic materials such as geosynthetic clay liners (GCL) need more exploration to study their behavior for mining closure activities for long term.

The third option basically consists on the derivation of runoff and collection of contact water, mainly infiltration. These methods are detailed in hydrological stability issues chapter.

Mitigation of ARD and monitoring

If ARD is generated, active and passive technologies are necessary increase pH and remove solutes to accomplish water quality standards for discharge or reutilization. This treatment involves passive and active closure criteria that largely increase closure costs. Improved methods of prevention and control substantially reduce ARD treatment. TSF design must consider the collection of this water, avoiding impacts on soil, groundwater and superficial water. After closure, monitoring of groundwater and superficial water downstream of TSF is an important issue to control possible flows of infiltration during operation and after final closure. However most monitoring plans don't last more than 10 years when the real effects of ARD can be noticed even after hundred years.

Ongoing laboratory testing of tailings and collection of supernatant pond and seepage water samples from TSF during operation and after closure of mine is needed to verify control methods and TSF geochemical stability.

PHYSICAL STABILITY ISSUES

Climate and seismic site conditions need to be considered for the closure of surface tailings disposal, focusing on provide robust structures against the following issues: (i) internal water erosion (piping), (ii) external water erosion (runoff), and (iii) wind erosion.

Erosion

In addition to influencing ecosystems (soil, water bodies, flora and fauna), dust emission can negatively affect human health through particulate matter (PM10) pollution. At TSF closure stage, a cover material is needed to manage runoff erosion and create an appropriate ground surface for project reclamation. Dust emission control play an important role in closure design and a proper implementation will provide the primary control mechanism to meet regulatory air quality requirements. Some other dust control alternatives are: soil cover, top soil/re vegetation cover, phytostabilization, binder material or chemical agglomeration, and wind mitigation civil work structures.

Dam Stability

The design of TSF embankment must consider the damage from repeated occurrences of extreme rainfall and earthquake events as well as progressive processes like internal erosion, which in conjunction degrade dam stability in the long term. For these reasons, a periodic inspection program is needed in the post closure stage (ICOLD, 2011), which includes the following activities:

- Evaluate dam stability, considering gentle slopes and benches.
- Evaluate geotechnical instrumentation (mainly piezometers, accelerometers, and underdrain collection sump).
- Evaluate the compaction of dam crest and slope benches.

However, it is important to consider that the potential for piping, filter clogging or creep deformations over hundreds of years cannot be appreciated by available dam safety evaluation methods (Szymanski, and Davies 2004) and designs need to consider long term civil works at TSFs beyond closure stage.

Geologic Hazards

In the indefinite future TSFs will be subject to the full suite of geomorphic processes operating at their sites. These include landslides and debris flows with river damming, characteristic of the Andes. Like the occurrence of these extreme events, the damaging effect of these processes is only a matter of time, and their recurrence rate is a factor particularly difficult to predict for large-scale geologic phenomena. Even benign processes of alluvial deposition will eventually fill water conveyance facilities unless they are continually cleared of sediment and debris. For these reasons, periodic surveillance programs need to be implemented for post closure stage at TSFs (ICOLD, 2011), to evaluate potential geologic risks and build rock falls and debris flow protection structures.

HYDROLOGICAL STABILITY ISSUES

TSF has to be designed for given annual hydrological conditions or more correctly for a range of conditions in which the storm events are statically included. Decants, pumping systems, spillways, piping, and treatment plants need to be sized for such criteria. However, TSF still has to able to cope with individual extreme runoff events, as they occur when the pond is at its maximum operating level. For closure design (long term) it is necessary to consider events that might come from an extremely heavy rainfall, snowmelt, debris/mud flows, climatic change, or a combination of them.

Freeboard

An adequate approach to closure design is to use two design floods: an environmental design flood (EDF) and a facility design flood (FDF). The EDF is typically from a storm with a finite return period of say 10 to 100 years, or it may be a rainfall/snowmelt event. It is the maximum storm event which still does not result in an unscheduled discharge of water to the environment. The flood from the EDF is retained at TSF, within a freeboard allowance below the invert of an emergency spillway, and managed within the normal operation of TSF basin. For this reason, a maximum operating water level (MOWL) should be specified in conjunction with the EDF. The MOWL should not be exceeded under normal operating conditions. The MOWL should provide for adequate freeboard to store the EDF without discharge over the emergency spillway. However, water storage within the TSF may be contradictory with dry cover integrity and may enhance water infiltration through the tailings deposit. This may result in consequent drainage with high sulfate and/or metal concentrations, for these reasons, is necessary to define dry cover zones (tailings beach against dam), wet cover zones (pond), and a maintenance dry cover program. Physical stability must be the primary objective of long-term closure. No means for controlling ARD can succeed unless the tailings are first made to stay in one place, and anything that violates this provision will necessarily compromise all others.

Spillway

The overtopping of a dam could result in a catastrophic failure, extensive erosion, loss of tailings to the environment, a very large uncontrolled spill of water, and even the complete emptying of the pond. For these reasons, an emergency spillway is a safety measure, which must be included in every TSF for closure, to handle unforeseen events and to protect the environment. Under any circumstance should tailings be allowed to escape from a basin or a dam is allowed to overtop. The FDF must be chosen to ensure that this does not happen. The routed FDF is used to size the emergency spillway. For a tailings basin, it is frequently based on the largest possible storm resulting from the probable maximum precipitation (PMP) which might or might not occur in conjunction with snowmelt. Robust spillways need to be designed and constructed. Floods in excess of the EDF are either allowed to spill unimpeded (very large storms) or to spill slowly with a reduced retention time through the emergency spillway. If spillage cannot be tolerated under any circumstances, then the EDF and the FDF have to be the same.

The following figures show the management of storm flow/freeboard concept and a spillway civil work.

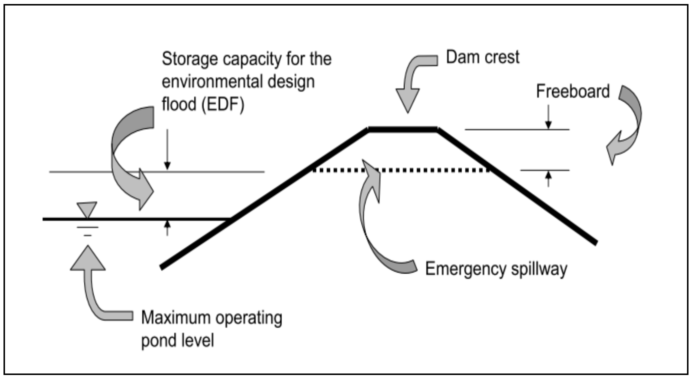

Figure 1 Management of Storm Flows (Golder, 1989)

Figure 2 Spillway and Energy Dissipators

Perimeter Diversion Ditches

Collection and diversion systems for non-contact water (runoff water), consisting of perimeter ditches is required as part of TSF design. For the closure and post-closure phases, it is important to provide lined diversion ditches with long term erosion-resistant materials such as geoweb/concrete solution, GCL liner, or reinforced concrete. Soil excavated ditches without liners are not recommended for TSF closure stage. A periodic inspection program needs to be carrying out for review the integrity of the diversion ditches.

Seepage Collection System – Collection/Polishing Pond

The seepage collection system consists of a cutoff trench and a robust underdrain system. Both systems convey the TSF contact water to collection geosynthetic lined ponds, where water quality is controlled. If the water quality meets the standards, it is possible to discharge it to natural courses. If it is not, water needs to be treated. The installation of downstream monitoring wells is recommended to control periodically the water quality on the TSF on post-closure phase. Polishing ponds or sedimentation ponds are designed to increase the environmental compatibility and quality of effluents from preceding treatments. The water in the reclaim pond is either sent to treatment/polishing ponds for discharge to the environment. Some reclaim water can be sent to evaporation ponds or sprays if the climate is suitable.

Water Storage Dams - Upstream of TSF

An adequate approach for closure design of TSF to control large floods and runoff is to manage water with a high dam storage capacity and a separate water-control dam located upstream of the TSF. Some advantages are: (i) buffering of probable maximum flood (PMF), (ii) controlled diversion, and (iii) promote non contact water.

TSF CLOSURE CASES

El Indio TSFs - Andean Region of South America - Chile

El Indio copper-gold mine is located in the Chilean Andes approximately, 180 km east of La Serena City. The climate is typical of Andes mountain region of dry conditions, with variable winter precipitations (May – September), mainly as snow. On the operation phase the mine had an open pit and underground activities, with two waste rock dumps, three process/metallurgic plants, and three tailings storage facilities.

The mining company negotiated a voluntary agreement with the Chilean region IV regulatory authorities after 20 years mine lifetime to carry out the closure stage of El Indio Mining project, as there was no legislation yet in place in Chile focused on mine closure. One of the key components of the closure plan was surface water management works developed under the overall objective of "establish a physically and chemically stable drainage system with minimal maintenance and monitoring requirements" (Robledo and Meyer, 2007). As consequence of mining activities, Malo River stream was modified in several sectors with diversion civil works. The main closure activities were: (i) restoration of Malo River drainage system in the process plant area and on TSFs by the construction of engineered lined channels (lined with rockfill and cobblestones), and (ii) abandonment of the existing Malo river diversion system.

Tailings and waste facilities managed in El Indio Mine were: (i) Pastos Largos TSF, (ii) El Indio TSF, (iii) dry tailings modules (filtered tailings), and (iv) sedimentation pond (polishing pond). Specific closure works at the TSFs were considered including surface grading, placement of a cover to prevent hydraulic and wind erosion, and the construction of spillways to manage storm flows. The sedimentation pond is located at Malo River downstream of TSFs stored approximately 66,000 m^3 of sediments (As, Pb, and cyanide among others). Sediments were transported by haul trucks to Pastos Largos TSF for disposal. The pond was removed and the Malo River was restored in its natural stream.

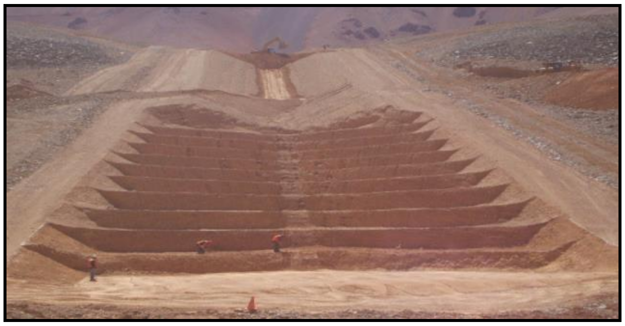

Figure 2 Malo river closure civil works construction (Saez, 2011)

Figure 3 Malo river closure civil works finished

(Saez, 2011)

Figure 4 Filtered TSF – Operating phase (Saez, 2011)

Figure 5 Filtered TSF – Closure phase (Saez, 2011)

Constructed diversion ditches were lined to reduce infiltration of surface water into mine tailings materials and to prevent capture by underground mine workings, with the intent to minimize chemical loading impacts to water. A geosynthetic clay liner (GCL) was selected for lining in most cases. The following pictures show some overall views of closure civil works at El Indio TSFs:

Figure 6 Filtered TSF – Closure construction phase – civil works (Saez, 2011)

Casapalca TSFs – Andean Region of South America - Peru

The Casapalca polymetallic mine is located in Peruvian highlands, approximately 113 km east of Lima city, Peru. The mine is composed by underground activities, and is near to the Rimac river, at an elevation of approximately 4,100 m above sea level. The climate is typical of Peruvian Andes conditions. Annual precipitation is approximately 700 mm with essentially this entire amount falling in the rainy season (November – March). To prevent and reduce the risks for human health and the environment, one of the key components of the closure plan was surface water management works developed under the overall objective of "establish a physically and chemically stable drainage system to Rimac River" (Estrella, 2008). As consequence of mining activities, the stream of the Tacpin creek was modified in several sectors by using a constructed diversion civil works. The main closure activities in the middle part of the Tacpin creek basin were: (i) restoration of Tacpin stream surface drainage channel in the land area and across tailings facilities by construction of engineered lined channels, and (ii) abandonment of the existing Tacpin stream diversion tunnel system.

The tailings waste facilities managed in the Casapalca Mine were: (i) Tablachaca I, and (ii) Tablachaca II. Specific closure works at the TSFs included surface grading and placement of a cover (organic soil layer + clay layer + gravel layer + HDPE layer) to prevent: (i) hydraulic and wind erosion, (ii) oxidation of sulphide tailings, and (iii) physical stabilization of TSF slopes. Hydraulic civil works constructed with reinforced concrete were: (i) diversion ditches to collect no contact water, (ii) diversion tunnel (rock wall reinforced), and (iii) Tacpin stream intake structure to divert runoff to diversion tunnel. Like a post closure activities revegetation was applied, with native plants from the site.

The following pictures show some overall views of closure civil works at Tablachaca TSFs:

Figure 6 Construction of closure civil works (Huaymanta, 2011)

Figure 7 Closure civil works finished (Huaymanta, 2011)

Figure 8 Tablachaca TSF before closure stage (Estrella, 2008)

Figure 9 Tablachaca TSF after closure stage (Estrella, 2008)

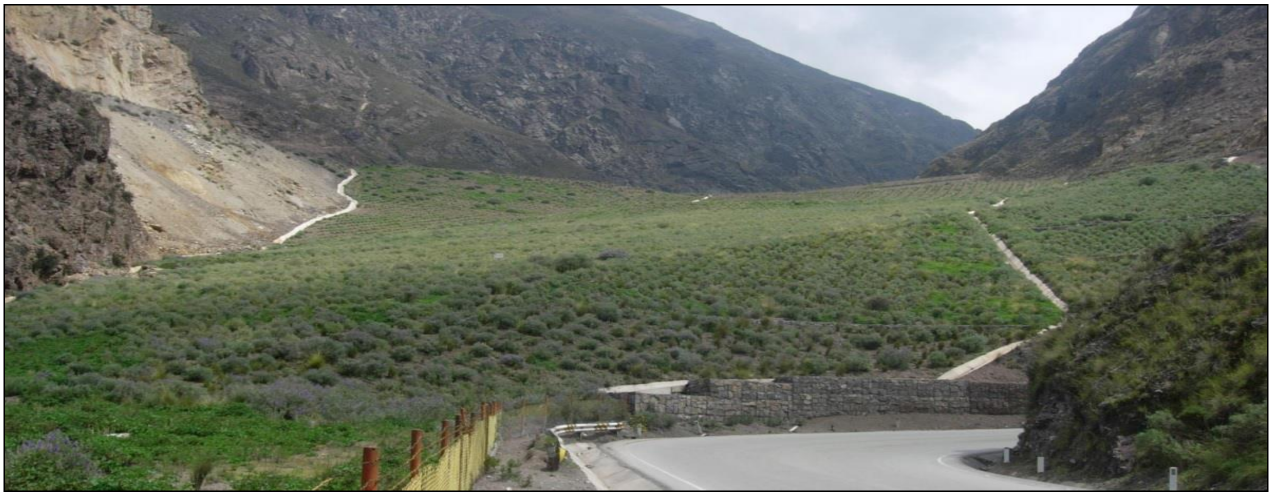

Figure 10 Tablachaca TSF closure overview (Estrella, 2008)

In both TSF closure cases the application of the concepts of closure, decommissioning, cover implementation, collection and diversion of non contact water and channeling of water streams are valuable issues. However, it is important to consider that tailings disposal on a riverbed is prone to geological and hydrological hazards on extreme flood events and geodynamic events. It is relevant to consider a periodic OMS program (operation, maintenance and surveillance) and ISR/DSR programs (Inspection Safety Review/Dam Safety Review) after the closure activities to monitor and control the closure TSF performance at these study cases (ICOLD, 2011).

CONCLUSIONS

The main goal of long-term closure is to achieve "walk-away" conditions that assure physical, hydrological and chemical stability without the need of long-term monitoring and maintenance. This objective depend on the motivation and ability of authorities to deal with mining wastes after decades, and even centuries, avoiding to pass the burdens of today's resource extraction to future generations who will inevitably receive the impacts of these passives (Tabra and Lange, 2014).

One of the main challenges in closure design for TSF is probably their capacity to deal with extreme events (hydrological and seismic). For surface tailings disposal, water management related with high surface water flows should consider the rapid evacuation of water, minimizing erosion and instability, and temporal water storage that requires specific design to minimize infiltration. Civil works and control systems for TSFs must be designed in the early stages of a mining project with conservative criteria and robust structures, thinking about the perpetuity of this component and projecting a periodic schedule of maintenance and restoration in the post-closure stage (Cacciuttolo et al., 2014).

Geochemical stability is a relevant part of a TSF project, particularly if tailings contain acid-generating behavior, because these materials can degrade the strength properties of cycloned tailings sand dams and borrow dams, increasing dam failure risks and generating ARD. In general, mine residues that interact with the environment should be inert to materials and chemicals already in the same ecosystem. If mining wastes are not inert they should be isolated and in a form that is compatible with the adopted waste management technique, the sensitivity of ecosystem and social context.

In recent years, there have been significant advances in physical and hydrological stability of TSFs (investment effort and better decisions on site selection and use of technology for tailings management). However it still remains to devote more time to understand the action of tailings geochemistry and make greater efforts to prevent, control and mitigate ARD on TSF in the long term.

A long-term closure requires going beyond the usual engineering perspective, with an interdisciplinary approach taking in consideration all points of view in important decision making such as site disposal, method of disposal, TSF design, control methods, contingency plans, among others. In most cases, an initial high inversion is more rentable in the long term. Mining, mineral processing and waste management technologies, which offer improved environmental and social performance, and smaller surface footprint, should be preferentially adopted. Also, opportunities for re-use of waste material should be pursued when practicable.

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