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# Design, Construction and Operation of a Large Centerline Tailing Storage Facility with High Rate of Rise

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## Abstract

In 2004, Sociedad Minera Cerro Verde S.A.A. (SMCV) undertook final design and construction of the Primary Sulfide Project involving construction of a 108,000 metric tonnes per day (mtpd) concentrator at its Cerro Verde Copper Mine, located near Arequipa Peru. An important component of the project is the tailing storage facility (TSF) which was permitted as a centerline method tailing embankment with an ultimate height of 260 meters above the foundation at the centerline and 300 meters above the downstream toe. The Primary Sulfide Project was designed and constructed in a 24 month period and was commissioned in November 2006.

The Cerro Verde Mine is located in a region of high seismicity dominated by earthquakes occurring along the Peru-Chile Subduction Zone, which has a history of producing very large earthquakes that could cause significant shaking at the TSF site. The TSF is positioned immediately downstream of the concentrator in drainage called Quebrada Enlozada. The Starter Dam for the TSF is an 85 meter high zoned rockfill embankment. The TSF embankment is raised above the starter dam crest using centerline method construction. Underflow sand that is produced by a two stage cycloning process is placed in 30 centimeter lifts and compacted. During the first four years of operation, the TSF embankment reached half of its ultimate height. A debottlenecking project was completed at the concentrator in 2010 to increase the concentrator throughput by 12,000 mtpd to its current capacity of 120,000 mtpd.

This paper presents the design basis and criteria that were adopted for the Quebrada Enlozada TSF, provides a summary of the main design components, and discusses operation of the facility during the first 5 years of its projected 22 year life. Particular focus is placed on special considerations to accommodate the very high raise rates that were experienced in the initial years of TSF operations. The primary technical and operational challenges and the successful implementation of engineering and construction solutions are described.

## Introduction

The increased interest in developing large low grade ore deposits has lead to the requirement to build equally large Tailing Storage Facilities (TSF). The commissioning of new, larger and more efficient milling and process equipment allows the implementation of large production rates. This leads to the requirement to construct TSFs not only large in terms of capacity and size, but also in rate of rise, especially in steep mountainous areas.

In 2003, Sociedad Minera Cerro Verde S.A.A. (SMCV) undertook an evaluation of the feasibility of the development of the Primary Sulfide Project involving construction of a 108,000 mtpd concentrator at its Cerro Verde Copper Mine, located near Arequipa Peru. The required capacity for the TSF to support the planned mine expansion was just over 1 billion tonnes of tailing. At that time there were a handful of TSFs in the world that were designed to store close to a billion tonnes of tailing materials, to reach over 200 m embankment height and achieve a rate of rise of over 20m per year.

The scale of the project combined with the site characteristics (high seismicity and dry climate) required a significant effort to select the best site, appropriate embankment type and a suitable disposal method. More than 10 sites were evaluated and compared in terms of technical, environmental, social and economic features and the Quebrada Enlozada site was selected as the best TSF site. The embankment selection study included consideration of centerline and downstream embankment types, and a variety of construction materials including cycloned tailing underflow, mine waste rock and quarried rock. Due to the relatively low efficiency ratio of the selected site, water conservation considerations and economic factors, a centerline embankment type constructed of compacted cycloned tailing underflow was selected as the best alternative.

Conventional, thickened, paste and filtered tailing disposal methods were also evaluated in the process of selecting the best TSF option for further development. The main considerations were water conservation, stability of the facility, potential impacts to the environment (seepage, dust, flora and fauna), and operational practicality. The large production rate made the use of tailing filtering and dry stacking, as well as the application of paste, not practical at this time. Thickening of the tailing using conventional thickeners was adopted to reduce the recirculated water and potentially reduce the water losses.

As a result of the alternatives studies, a centerline TSF constructed of compacted cycloned tailing sand in Quebrada Enlozada was selected as the TSF for further development.

This paper describes the process and challenges met during the final design, construction and operation of the Quebrada Enlozada TSF.

# Site Characteristics

The Cerro Verde mine is located approximately 30 km south of the city of Arequipa in Southern Peru, on the west slope of the Andes Mountains, in the south segment of what is referred to as the Coastal Batholith. The mine is situated on a plateau that has been eroded and dissected by numerous dry stream valleys to form locally steep and rugged topography. Elevations in the region range from about 2,300 to almost 3,000 m above mean sea level (amsl).

The climate of the area is mild and arid with temperatures fluctuating between 10° and 24°C and average annual precipitation of approximately 35 mm. The rainstorms occur seasonally and are typically of short duration and high intensity. Over 90% of the annual rainfall is recorded during the months of January, February and March. The recorded evaporation at the project site exceeds the precipitation over 60 times. The estimated average annual evaporation rate is about 6.1 mm/day. The humidity ranges from about 30% in July to about 70% in February.

The TSF site is located in a region of high seismicity dominated by earthquakes occurring along the Peru-Chile Subduction Zone. Based on the results of deterministic and probabilistic seismic hazard evaluations, the Design Basis Earthquake (DBE) selected for the design was defined as the controlling Maximum Credible Earthquake (MCE) occurring along the Southern portion of the Peru-Chile subduction zone at a source-to-site distance of about 65 km from the TSF site. The DBE was specified as a moment magnitude 9.0 (Mw) megathrust earthquake producing a peak horizontal acceleration at the top of bedrock of 0.47g at the TSF site. The ground motions for the DBE were defined at the 84th percentile level over a broad frequency range.

The geology at the TSF is composed of volcanic ash, alluvium, and colluvium overlying metamorphic, volcanic, sedimentary, and intrusive igneous bedrock. In general, the foundation is characterized by strong to very strong rock with relatively low permeability. Alluvium and Colluvium deposits are found mainly in the valley bottom areas and lower valley slopes. The Colluvium is generally a thin veneer near the bottom of steep slopes. The Alluvium is located in the valley bottom and ranges in thickness from a few meters at the TSF embankment to over 20 m downstream of the TSF.

# Design and Construction

Final design of the TSF began in late 2004 and was completed in 2005. Construction of the Starter dam began on the first design package in early May 2005 while work continued on the remaining design packages.

The main objectives adopted for the TSF design were:

- To store the tailing materials in an environmentally responsible manner.
- To satisfy internationally accepted stability criteria for embankment construction in areas of high seismicity.
- To satisfy all relevant Peruvian regulatory requirements associated with construction of the TSF.
- To follow the concept of zero discharge, which means the use of proven and feasible state-of-the-practice engineering and technology for the design, construction, operation and closure of a facility, in order to minimize any discharges from the facilities to the environment.

The principal design basis and criteria adopted for the Quebrada Enlozada TSF are presented in Table 1.

**Table 1: Cerro Verde TSF – Design Basis and Criteria**

| | | |
|---|---|---|
| Production Rate | 108,000 t/d | Ramp-up schedule for 1st 6 months |
| Percent Solids from Tailing Thickeners | 55% | Range 50-60% |
| Percent Fines in Tailing Slurry | 67.5% | Weighted Average Tailing Sample |
| Average Compacted Dry Density of Underflow | 1.58 $t/m^3$ | 98% of max dry density (ASTM D 698); the 1.58 $t/m^3$ value will vary for different tailing materials over the life of the mine. |
| Start-up Water Requirement | 1,000,000 $m^3$ | To provide water for the start of the operations |
| Flood Storage Requirement | PMF | Contain within impoundment, min 100 m from embankment crest during flood conditions. |
| Seismicity/Earthquake Load | MCE | Canadian Dam Association, Dam Safety Guidelines, 1999 |
| Min Freeboard (Vertical distance between embankment crest and max impoundment elevation) | 3 m | To provide sufficient flood storage and accommodate anticipated earthquake induced settlements. |
| Min Static Factor of Safety (FOS) | 1.5 | Canadian Dam Association, Dam Safety Guidelines, 1999; USBR, Chapter 4, 1987 |
| Post-earthquake FOS | 1.2 | ANCOLD Guidelines, 1998; USBR, Chapter 13, 2001 |

# Design Concept

The TSF was built in the Quebrada Enlozada immediately north of the processing plant, as is shown on Figure 1.

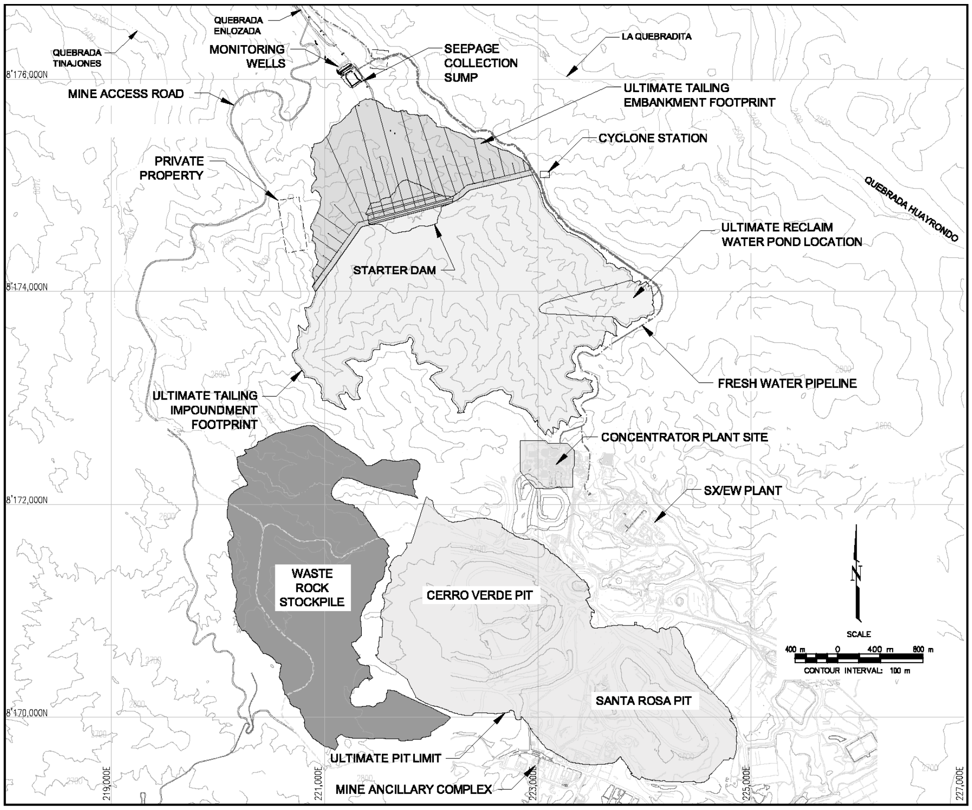


**Figure 1: TSF Plan View**

The TSF consists of an 85 m high zoned rockfill Starter Dam, a 260 m high embankment constructed of compacted cycloned tailing sand by the centerline method, and a tailing impoundment that will cover an area of approximately 453 Ha at its ultimate configuration. The base of the Quebrada Enlozada at the location of the Starter Dam is at an approximate elevation of 2400 m above mean sea level (amsl). The elevation of the processing plant is about 2,700 m amsl. The Starter Dam crest elevation will be at 2485 m amsl and the ultimate embankment crest elevation will be 2660 m amsl. A cross-section of the TSF embankment is shown on Figure 2.

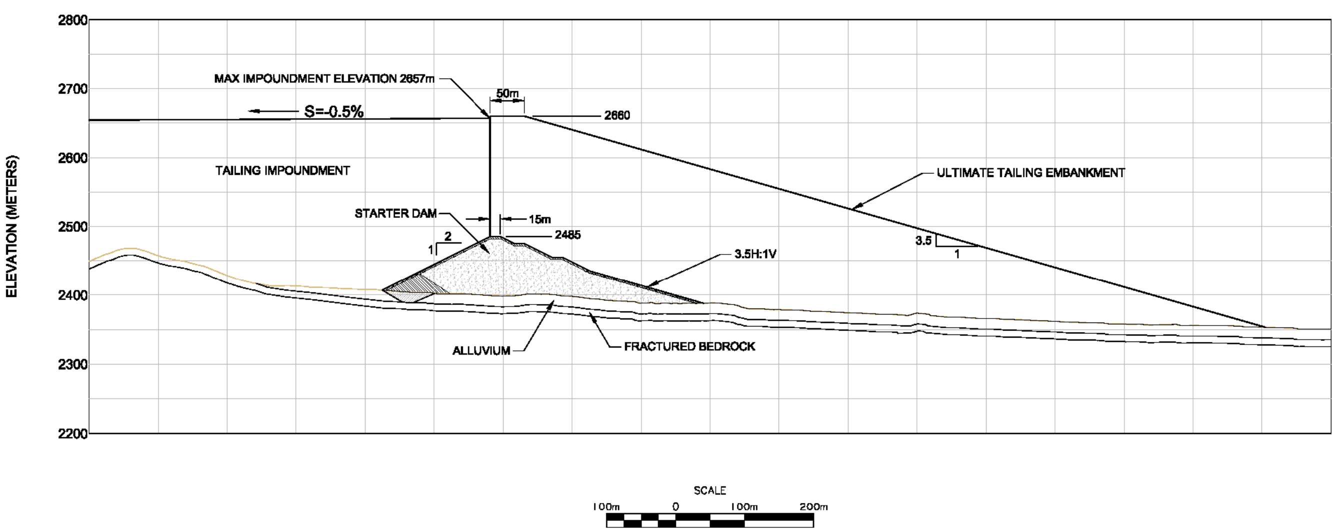


**Figure 2: TSF Embankment Cross-Section**

A reclaim water pond is maintained at the rear (upstream) end of the impoundment. Water from the reclaim water pond is recycled to the processing plant for reuse and to the cyclone station for dilution. Seepage from the embankment is collected by a network of finger and blanket drains and conveyed to a Seepage Collection Sump located immediately downstream of the ultimate embankment toe. The water is then pumped from the sump to the cyclone station and reused as dilution water or can be conveyed to the processing plant.

## Design Challenges

The main challenges faced during the design of the TSF were unprecedented embankment height, low impoundment to embankment ratio and relatively fine projected tailing grind, high rate of rise and ability to keep the embankment construction ahead of the impoundment raise, maximizing the water reuse and minimizing the water losses, and design/construction schedule constraints. A description of these challenges is provided in the following paragraphs.

### Dam Height and Limits of the Testing Equipment

One of the requirements in selecting a site, embankment and deposition method was to provide storage for approximately one billion tonnes of tailing materials. To achieve this goal, the embankment height at the Quebrada Enlozada site has to be 260 meters at the centerline and 300 meters above the downstream toe. This put the Quebrada Enlozada TSF among the tallest tailing embankments that had been designed at that time, if not the tallest. The design of all high embankments comes with challenges, which increase significantly in areas of high seismicity. Strength characterization, evaluation of the behavior of the compacted underflow sand, and potential particle breakage were some of the challenges faced during the design process. These factors lead to the need for special testing equipment (triaxial and direct shear) to evaluate the effects of the very large loads on the strength of the compacted underflow sands that were to be used for construction. Details on the testing program are presented in a paper entitled “Effect of High Confining Stresses on Static and Cyclic Strengths of Mine Tailing Materials”.

### Low Efficiency Ratio and High Rate of Rise

The low efficiency ratio of the TSF (impoundment volume/embankment volume = approximately 3), combined with the relatively high production rate lead to a required high rate of rise of the facility in the initial years of operation. In addition, the projected tailing grind was relatively fine with a P80 size of 125 microns and 67.5% passing the No. 200 sieve. Cyclone simulations estimated that underflow recovery with two stage cycloning would be approximately 34%. The estimated underflow recovery, a cyclone operating time between 85 and 90%, and freeboard requirement of a minimum of 3 m were the main inputs to the material balance analysis performed to estimate the required starter dam height.

The main design requirements for the Starter Dam were as follows:

- Provide sufficient storage for the tailing overflow until the embankment shell constructed of compacted underflow tailing materials reached the crest of the Starter Dam.
- Provide storage for the PMF during the first year of operation.
- Provide storage for at least 1 million cubic meters of start-up water.
- Minimize seepage from the start-up water pond and the tailing overflow materials through and beneath the Starter Dam.
- Satisfy filter criteria to limit the potential for piping of tailing materials through the Starter Dam.

- Provide access, accommodate tailing delivery and deposition systems, and facilitate the cycloned sand embankment construction from start-up through the first year of operation.

Based on the results of the material balance analysis and considering the design requirements, the required height of the Starter Dam was established to be 85 meters at the centerline, with a crest elevation of 2485 m. The main considerations in selecting the Starter Dam design slopes were stability, constructability and the properties of the borrow materials. The downstream slope of the Starter Dam is 3.5H:1V below elevation 2435 m to facilitate the initial underflow embankment construction at the start of operations and to begin establishing the design embankment slope (3.5H:1V). Based on stability considerations and required space to accommodate an underflow and an overflow jacking headers for tailing deposition, a 50 m wide crest was selected for the ultimate embankment. To reduce the Starter Dam volume, and provide space for installation of the underflow jacking header, a 15 m wide bench at elevation 2475 m was incorporated in the Starter Dam design.

The relatively low efficiency ratio and limited underflow availability were some of the reasons leading to the selection of a centerline rather than a downstream construction method. In addition, the centerline method was advantageous for the rapid rate of rise that was experienced during the early years of operation of the facility, because vertical raising of the overflow and underflow header pipes is less time consuming than raises for downstream method construction.

Selection of a jacking header system to accommodate efficient raising of the underflow and overflow header pipelines along the embankment crest was a critical design decision because of the very rapid raise rates in the first few years of operation. The jacking header consists of a steel frame that is mounted on steel posts on which it can freely slide to accommodate vertical raising by a system of jacks. One jack is located on each set of two posts (see Photo 1). The underflow is discharged from the underflow delivery line through spigots at about 2 m intervals. Raising the jacking header is coordinated with the embankment rate of rise and the deposition sequence. Clearance of a minimum of 4.5 m is provided at any one time beneath the jacking header structure to allow compaction equipment to move beneath it.

**Photo 1: Jacking Header**

## Maximizing Water Reuse

Maximizing the water reuse and minimizing the water losses were factors of a significant importance during the design of the TSF. Some of the water conservation measures incorporated in the design are described in the following paragraphs.

Minimum Size Pond

The tailing impoundment covers an area of approximately 453 Ha. After separation of the sands (underflow) at the cyclone station, the remaining fine tailing (overflow) is deposited into the impoundment, primarily adjacent to the crest of the TSF embankment. Occasionally, when the cyclone station is not in operation (e.g., for maintenance), the whole tailing stream bypasses the cyclone station and is discharged into the impoundment via the overflow pipelines. The tailing materials are discharged into the impoundment as per a deposition plan that was developed during design, which is included in the Operations Manual. One of the main objectives of the impoundment deposition is to manage the size and location of the reclaim water pond and to minimize development of isolated water ponds that would be inaccessible for recovery by the reclaim water system. A scalping cyclone station was commissioned after the second year of operation, as per the original design, to produce cyclone overflow for deposition at various strategic points around the impoundment perimeter to avoid development of isolated water ponds and to aid in managing the location and size of the main reclaim water pond in the southeast corner of the impoundment. The station is located at the upstream reach of the ultimate impoundment, close to the concentrator plant. The purpose of the station is to separate the coarser tailing particles in the produced underflow, which are put back to the whole tailing launder to the central cyclone station to avoid loss of sand that is a valuable resource for embankment construction.

Drain System

The embankment is underlain by an extensive drain system which is a critical element of the design because it promotes rapid drainage of the cycloned tailing sands, maintains the phreatic surface low in the embankment section and expedites recovery of water that drains from the underflow sands after deposition. The drain system within the estimated embankment limits for the first two years of operation was built as a part of the initial capital construction prior to the start of the operation of the concentrator plant. The embankment is being raised in lifts of compacted cycloned tailing sands concurrent with filling the impoundment. As the embankment is raised in height, its footprint is expanding downstream. Accordingly, the embankment underdrain system is being expanded in three subsequent phases as a part of sustaining capital construction.

Seepage Collection Sump (SCS)

Seepage collected by the network of finger drains and blanket drain within the footprint of the embankment is conveyed to a Seepage Collection Sump located immediately downstream of the ultimate embankment footprint. The Seepage Collection Sump provides a pond from which the collected seepage and tailing embankment stormwater runoff are pumped to the cyclone station or to the concentrator plant for reuse. The Seepage Collection Sump includes design components to minimize the risk of seepage from the TSF past the sump and into the environment and to satisfy the "zero discharge concept" criteria. The main design components of the Seepage Collection Sump are:

- An excavation through the alluvium across the valley down to fractured bedrock to create a sump.
- A geosynthetic liner on the downstream slope of the sump anchored into a concrete grout cap at the excavation bottom and side slopes.
- A grout curtain at the bottom of the excavation extending through the fractured bedrock into low permeability bedrock.
- A sump with a capacity to store runoff from the 100-year, 24-hour storm plus a small operating pond and operational flows to the sump during an assumed 12-hour power outage.
- A spillway designed to pass flows from the 500-year, 24-hour storm.
- Five monitoring wells located downstream of the sump to monitor groundwater quality. Four of the wells are equipped with pumps to intercept subsurface seepage that bypasses the grout curtain.

## Schedule Constraints – Multiple Design/Bid/Build Packages

A very aggressive 24 month schedule was adopted for design and construction of the Primary Sulfide Project including the concentrator and components of the TSF required for project start-up. These components included the Starter Dam, the drain system within the 2 year footprint, the seepage collection system, the tailing delivery system, the two stage cyclone station, and the reclaim water system.

Careful planning of the construction activities, durations, and the critical path schedule indicated that three separate, but coordinated design/bid/build packages were needed to meet the project schedule requirements. The first package included foundation preparation for the starter dam and material processing to produce drain and filter materials. Design for this package was prepared in about 3 months after notice to proceed with design, and construction began 2 months later after completing the bidding process, contract award and mobilization of construction equipment and personnel. The second and third design/bid packages were progressing at the same time. The second package included earthwork for all zones of the starter dam embankment. Design for this bid package was completed in the fifth month after notice to proceed. The third package included the seepage collection and drain system, and utilized drain and filter materials produced by the package one contractor. It was convenient that the first and third packages were awarded to the same contractor.

Earthwork for the starter dam was programmed to be completed in 14 months. The actual construction was completed one month ahead of the scheduled completion date. Critical to the success in achieving this construction schedule was self performance of the rockfill placement and compaction by the mine with large mining equipment, and performing earthwork activities for more detailed activities (defined as placement in lifts less than one meter in thickness) with contractors.

## Instrumentation

Embankment instrumentation consists of piezometers installed in the Starter Dam, in the foundation, in the drains, and in the embankment underflow. The purpose of these piezometers is to monitor pore water pressures and the phreatic surface within the embankment and foundation materials. Additional piezometers are being installed throughout the operating life of the TSF in accordance to the design and construction permit approved by the Ministry of Energy of Mines of Peru.

In addition, two accelerometers are located just downstream of the ultimate embankment footprint to monitor ground accelerations during seismic events. One of the accelerometers is placed on bedrock and the other on alluvium. The data registered in these accelerometers is used to verify the seismic parameters utilized in the design of the TSF.

A continuous flow-measuring weir is installed immediately upstream of the seepage collection sump. The measuring devise consists of a V-notch weir installed in a concrete flume. Flow rates are calibrated to the water level in the weir which is measured by a pressure transducer submerged upstream of the weir and recorded in the SCADA system.

# Operation Challenges and Successes

A great deal of effort was dedicated to planning of both start-up and operation of the TSF. An operations and maintenance manual was prepared to provide guidance on requirements for every aspect of the facilities from underflow deposition and compaction to pond management and deposition scheduling.

Prior to the Primary Sulfide Project, a smaller concentrator and leaching were the main processes used to extract copper from ore at the Cerro Verde Mine. Therefore, start-up of the concentrator and TSF involved significant effort to hire and train employees that were new in their positions. In addition, the Quebrada Enlozada TSF is a relatively complicated facility with two stage cycloning, compaction of the underflow sand embankment, very large earthwork quantities/production rates, and very large raise rates. The project team of the Owner's Project Development and Operations groups and the Engineering team did an exceptional job of planning and organizing the resources that are required for success.

The Operations and Maintenance manual was developed during detailed engineering and design and has proven to be a critical part of the success of both the start-up and subsequent operation of the TSF. The manual provides very detailed descriptions of how to initiate underflow deposition as well as a month by month deposition rates based on detailed material balance analyses. The material balance analyses are being recalibrated and updated during the operation of the facility to reflect actual mine production and measured values.

## Embankment Cross Section and Construction Process

The tailing embankment is constructed by the centerline method over the Starter Dam to develop the ultimate configuration shown on Figure 2, using tailing underflow produced by a two-stage cycloning operation. The embankment has a crest width of 50 m and a 3.5H:1V downstream slope. Photo 2 Shows the TSF embankment with a crest elevation of approximately 2535 masl.

**Photo 2: TSF Embankment Viewed from Left Abutment**

The embankment is raised in lifts of compacted cycloned tailing sands concurrent with filling the impoundment throughout the operational life of the facility. A minimum of 3 m of freeboard between the embankment crest elevation and the elevation of the impounded tailing against the embankment is to be maintained at all times.

The process of embankment construction involves three basic steps: 1) deposit underflow tailing materials in a loose 0.3 m thick layer, 2) allow the deposited underflow to drain, and 3) compact the drained underflow materials to 98% of the maximum dry density per ASTM 698.

The underflow sands are discharged in a consistent manner along the embankment crest beginning at one end and progressing towards the other end. The tailing underflow deposition along the downstream slope is accomplished in a manner to promote a "sheet-flow" and prevent erosion of the previously placed and compacted underflow tailing materials. The underflow is discharged through spigots that are mounted on the underflow delivery line installed on the jacking header system.

## Rate of Rise, Compaction, and Drainage

The maximum ultimate embankment height of approximately 260 m at the embankment centerline (crest elevation 2660 m) will be reached after about 22 years of operation at the initial production rate of 108,000 t/d. The ultimate embankment length will be approximately 2.5 km. The impounded tailing material upstream of the starter dam reached the starter dam crest in about one year, as planned.

The rate of rise above the starter dam crest ranges from a high of over 20 meters in the second year of operation to about 4 meters in year 22.

The rapid rate of rise in the early years of TSF operation required careful planning, identification of very efficient construction methods, and incorporating design specifications and components that could meet the significant challenges posed by the high rate of rise. This lead to the following specifications, considerations and project components that were key to the success of the project:

- Specifying a maximum fines content of 15% in the underflow to promote rapid drainage of the underflow sands
- A two stage cycloning system to produce the quantity and quality of material required
- Mounting the underflow and overflow header lines on jacking header systems to accommodate efficient and rapid raising of the headerlines without interruption.
- An extensive drainage system to promote rapid drainage of the cycloned tailing sands and to maintain the phreatic surface low in the embankment section
- A barge pump system configured to accommodate rapid rates of rise in the first years of operation

## Limited Embankment Face Area at Start-Up

At start-up, the area of the downstream face that was available for underflow deposition and compaction was very limited. Deposition planning by MWH indicated that it would be critical to achieve 90% cyclone operating time and that in order to achieve this high cyclone station utilization early on, underflow deposition in additional areas would be required. This was achieved by providing an “excess sand line” to deliver underflow from the cyclone station to the valley floor so that the cyclone station could continue to operate when area was not available for deposition on the downstream face of the dam. Photo 3 shows underflow deposition onto the lower portion of the downstream face using spray bars that were fed from the crest and onto the drain blanket in the valley bottom from the excess sand line. Initially, the underflow was spread and compacted in a layer several meters thick on top of the drain blanket. Subsequently, the underflow was “stockpiled” above compacted base and then excavated with a loader and hauled to areas where drain and filter layers required covering with underflow placed mechanically before receiving hydraulic deposition of underflow. This system proved to be a huge success and enabled achievement of the necessary cyclone operation time.

**Photo 3: Starter Dam and Initial Underflow Deposition**

## Erosion of Drain and Filter System

Experience has shown that hydraulic deposition of underflow slurry directly on drain and filter systems causes erosion damage on these critical elements of the facility. For this reason, the design specified that three to four 30 cm lifts of underflow sand must be placed and compacted mechanically before hydraulic deposition was to occur. This provision was very successful in minimizing erosion of the drain and filter system. Other practices that helped to minimize drain and filter erosion were to deposit underflow only during daylight hours in areas where conditions made erosion a higher risk, and to maintain the underflow slurry density at 70% by weight or higher.

## Rapid Barge Movement

During the first year of operations, the reclaim water level increased about 50 meters from the level of the start-up water pond to near about 15 meters below the starter dam crest. During this period the barge travelled a distance of approximately 600 m. Considering the minimum pond depth requirement for pump operation and the requirement to maintain a small pond, the reclaim barges had to move frequently during this period. Careful planning and execution of these movements made this difficult task a great success. In addition, it should be noted that two barges were utilized so that one could remain in operation to supply water to the concentrator while the second one was inoperable during its movement.

### Selection of Compaction Equipment

Operating on slopes as steep as the 3.5H:1V downstream slope is a challenge for some types of compaction equipment. For this reason, the spread of compaction equipment includes several smooth drum vibratory compactors that are towed by Caterpillar Model D6 dozers in addition to self propelled smooth drum vibratory compactors. This combination has been very effective, as steeper areas can be compacted by the towed compactors and flatter areas and the embankment crest can be efficiently compacted by the self propelled compactors that have more difficulty operating on steep slopes.

### Planning of Underflow Deposition

A material balance with monthly time steps was developed to "build the TSF embankment on paper" throughout its entire 22 year period of operation. This type of planning was critical to identifying areas that require underflow placement and compaction at specific locations and rates at certain times in order to be able to maintain the required freeboard in all portions of the embankment. The topography at the Quebrada Enlozada TSF site has some very large side drainages that must be filled in advance on a very disciplined schedule in order to be able to maintain the embankment crest ahead of the impoundment level. This planning/scheduling effort has been very effective in achieving the required embankment configurations at all times.

### Water Recovery

The water balance produced by MWH during design indicated a peak makeup water requirement of 0.66 tons of water per ton of ore on average in the first year, reducing over time to about 0.44 tons of water per ton of ore. The actual makeup water requirement peaked at 0.67 tons of water per ton of ore and has reduced to about 0.38 tons of water per ton of ore making the Quebrada Enlozada TSF among most efficient in terms of water use of all conventional tailing storage facilities. This is especially significant considering the dry desert climate and the high evaporation rate in the area.

## Conclusions

The design and operation of a TSF in a highly seismic area, with a high embankment raised at high raise rates is faced with a number of challenges ranging from limitations of the laboratory testing equipment, and ability to maintain adequate freeboard, to achieving very fast rates of raising the tailing delivery lines on the embankment crest. Careful planning of all aspects of the operation was a key in the successful commissioning and operation of the Quebrada Enlozada TSF. Included in the Operations and Maintenance Manual were not only instructions on the operation and monitoring of the facility, but also a list of potential problems and contingency plans on how to deal with their potential occurrence. After almost 5 years of operating the TSF, its performance has closely matched the plan in all aspects. Attention to detail, diligence in proper operation of the facility, and recognizing the significance of such a large structure by the operators are all factors that are required for success on a project with this level of scale and complexity.

## Acknowledgements

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