Abstract

Unlike water retention dams, tailings dams typically are constructed in stages over the operating life of a mining project. The selection of an optimal design cross section for a tailings dam therefore is highly dependent on the operating requirements of the mine as well as the characteristics of the site and the tailings, amongst other factors.

The Collahuasi Copper Mine is located in the Andean Cordillera in northern Chile, at an elevation of over 4,100m a.m.s.l. The open pit mine is designed to ultimately supply ore to the concentrator facility at a rate of 120,000 metric tonnes per day. The tailings dam will be raised in stages to an ultimate height of over 100m and is designed to safely accommodate 1.8 Billion metric tonnes of mine tailings over the expected 45 year operating life of the mine.

This paper describes how the dam cross section was optimised to make the most cost-effective use of locally available borrow materials, mine waste rock and cycloned sand tailings for dam construction over the 45 year operating life of the mine.

Introduction

The Collahuasi Copper Mine is located on the eastern edge of the Altiplano in the Andean Cordillera of northern (Region I) Chile, at an elevation of over 4,100m a.m.s.l. The open pit mine is operated by Compañía Minera Doña Inés de Collahuasi S.A. (CMDIC), a joint venture by Falconbridge Ltd. of Canada, Anglo American plc of the UK and Mitsui of Japan. The joint venture Engineering, Procurement and Construction Management (EPCM) team of Bechtel and Davy International (now Kvaerner E&C) was responsible for design and initial construction of the mining complex. Golder Associates and ARCADIS Geotécnica (Golder-Geotécnica) designed the Collahuasi Tailings Impoundment and provided Quality Assurance monitoring during construction of the tailings starter dam. Subsequently, ARCADIS Geotécnica has been involved with raising the tailings dam.

The nominal design storage capacity for the tailings impoundment was 528 Million metric tonnes, deposited over an operating period of 25 years. However, to account for potential future ore reserves, the design was made sufficiently flexible to accommodate up to 1.8 Billion metric tonnes of tailings deposited over a 45 year operating life.

Feasibility level engineering for the tailings facility was completed in August 1995 and refined during an Interim Engineering phase, completed in September 1995, involving a series of eleven trade-off studies. These studies were aimed at optimizing dam design and tailings facility operation.

Final design of the tailings facility was completed in September 1997 and included three additional trade-off studies to further optimize dam location, construction materials
and process water recovery. Starter dam construction was completed in December 1997 and the facility began receiving tailings in January 1999. The facility is currently receiving tailings at an average rate of 66,000 metric tonnes per day (tpd).

Site Characterization

Characterization of the tailings impoundment included detailed geologic mapping and reconnaissance together with subsurface investigations and geophysical traverses. The subsurface investigations, consisting of 10 sampled boreholes (over 975 lineal m of drilling) and 41 test pits, together with in situ testing, were completed in three stages.

Geological and Geotechnical Site Characteristics

The tailings impoundment (Figure 1) will ultimately occupy an area of about 2,700 ha. The site is underlain primarily by alluvial soils, with colluvial deposits covering the lower slopes of Pabellón del Inca to the north, the foot of the Collahuasi Range to the west, and the Cordillera de Los Andes to the east. The alluvial soils in the upper 5 m are relatively coarse, pervious sands and gravels with varying amounts of silt and clay. Below this, the alluvial soils are more compact with higher fines content and are generally less pervious. Isolated deposits of fine grained lacustrine-alluvial soil are present. The underlying bedrock consists of Pastillos and Ujina Ignimbrites.

Rock outcrops at both abutments of the tailings dam with some colluvial (talus) deposits. The rock at the right (west) abutment is comprised of weakly to moderately weathered Ujina Ignimbrite overlying older Formación Collahuasi rhyolite lava flows which are hard, dense and highly fractured. At the left abutment, a thin cover (8 m) of Ujina Ignimbrite overlies dacitic lava flows which are highly weathered and porous in the upper 9 m and become moderately to weakly weathered with depth.

The main portion of the dam alignment is underlain by 15 m to 35 m of alluvial sands and gravels with up to 10% non-plastic, silty fines. The eastern portion of the alignment crosses lacustrine-alluvial deposits consisting of sand, silt and highly plastic silty clay, underlain (below a depth of about 2 m) by gravely sand and silty sand.
Site Seismicity and Volcanic Hazards

No potential for surface rupture associated with faulting at the site has been identified. All of the identifiable lineaments and faults are considered to be inactive.

Thirteen potential earthquake sources were identified within 150 km of the site. Two of these are associated with the Perú-Chile subduction zone, while seven are crustal faults and four are volcanic sources. The closest potential earthquake source is the Cerro Michincha volcano, 7 km to the east. Peak horizontal ground accelerations were established deterministically for the various sources. The far-field peak horizontal ground acceleration was determined to be 0.31g, associated with a magnitude 8.3 event at a depth of 100 km in the subducted Nazca Plate. A near-field acceleration of 0.21g was determined for a magnitude 6.0 event associated with the Cerro Michincha volcano.

Four potentially active volcanoes were identified within about 60 km of the dam site; Michincha (7 km east), Irruptuncu (23 km north), Aucanquilcha (31 km south) and Ollagüe (55 km southeast). Six volcanic processes posing a potential hazard were identified and assessed: lava flows, pyroclastic flows, debris flows, pyroclastic surge, ash fall and ground deformation. The effects of an ignimbrite eruption were not considered because the probability of such an occurrence was considered to be extremely low. In summary, the volcanic hazard at the site is low and Cerro Michincha presents only a minimal potential hazard to the tailings facility.

Site Hydrology and Hydrogeology

The Collahuasi Mine is located in an arid, desert climate. The average annual precipitation is about 150 mm per year, all of which occurs during intense, short duration storm events between December and March. These storms typically are localized events, confined within a particular watershed or even sub-watershed area. The average annual evaporation is estimated to be about 1,460 mm per year.

A site specific hydrologic evaluation was completed to determine design criteria (Table 1). The 100-year event was used for the design of operating spillways while a 10,000-year event was used for the closure spillway. The diversion channels were design using a 10-year return period event.

<table>
<thead>
<tr>
<th>TABLE 1: HYDROLOGIC DESIGN CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Period (years)</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>10,000</td>
</tr>
</tbody>
</table>

¹ Total runoff volume coming from the diverted area (56 km²).
² Peak flow from Yabricoyita Creek (representing 67% of the total watershed area of 37.3 km²).

Hydrogeological modelling completed for CMDIC indicated a very slight northward groundwater flow gradient, from the Michincha Basin towards the Coposa Basin, prior to start up. The flow towards the Coposa Basin is estimated to increase from a pre-
operations rate of about 240 l/s to about 300 l/s in Year 45. The modelling also predicts groundwater mounding of about 20 m near the dam, and 30 m to 70 m in the western portions of the impoundment, by Year 45. A potential for groundwater flow southward from the impoundment toward the Michincha Salar exists after Year 10. However, pumping from production wells downstream of the dam is expected to reduce potential impacts at the Michincha Salar.

**Tailings Characteristics**

**Physical Characteristics**

The total tailings currently being produced at Collahuasi is a sandy silt (ML) with between 57% and 72% fines (material passing the U.S.S. No. 200 sieve), a specific gravity of 2.77.

A laboratory testing program was completed during design to evaluate the physical properties of the tailings likely to be produced by cycloning operations (Table 2). The sand fraction was found to be a medium to fine grained, clean to silty sand (SP to SM) with 10% to 20% fines. The fine tailings fraction (slimes) was found to be a sandy silt (ML) with a 78% fines content and an IP of 12. Permeability testing of the sand fraction showed that increases in the fines content produced only negligible decreases in permeability, indicating acceptable drainage behaviour within that range of fines content.

<table>
<thead>
<tr>
<th>Tailings Fraction</th>
<th>$D_{200}$ (%</th>
<th>Settled Density (t/m³)</th>
<th>$C_V$ (x $10^{-2}$ cm²/s)</th>
<th>Permeability (cm/s)</th>
<th>Min. Density (t/m³)</th>
<th>Max. Density (t/m³)</th>
<th>C (t/m²)</th>
<th>φ (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Tailings</td>
<td>54 - 62</td>
<td>1.11</td>
<td>2.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slimes</td>
<td>72</td>
<td>0.96</td>
<td>1.35</td>
<td>1.47 $x$ 10⁻⁶</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sands</td>
<td>10</td>
<td>4.92 $x$ 10⁻⁴</td>
<td>1.21</td>
<td>1.61</td>
<td>1.7</td>
<td>35.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>4.4 $x$ 10⁻⁴</td>
<td>1.21</td>
<td>1.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2.54 $x$ 10⁻⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.31 $x$ 10⁻⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Geochemical Characteristics**

The results of Acid Based Accounting (ABA) testing during design phase indicated that in general the rougher tailings are not acid generating. Conversely the scavenger tailings presented the major source of sulphur and would have a moderate potential for acid generation. The last one is particularly applicable to the Rosario tailings. These tailings will be used to construct the sand dam wall.

However, given the highly alkaline process conditions, the tailings impoundment is expected to remain alkaline during operations unless it is allowed to drain and oxidize for extended periods. If necessary, acid generation could be controlled with lime addition.

To minimize the acid generation the sand dam will be constructed only cycloning rougher tailings (the sulphur content of the sand fraction is expected to be low). If it is
required, crushed limestone will be added to the cyclone underflow to cover the last 10 m of the sand dam.

The different behavior among rougher and scavenger tailings makes convenient to make a different tailings disposal for these materials: (i) the ultimate layer will be made of rougher tailings; (ii) the scavenger tailings will be accommodated in a specific area adding limes as a neutralizing agent.

Mine Operating Requirements

The Collahuasi Copper Mine plans to exploit two ore bodies (Ujina and Rosario-Huinquitipa) using open pit mining methods. The Ujina ore body is the first to be developed and is located about 10 km from the tailings dam site and a similar distance from the proposed waste dump sites. This location made the possibility of using waste rock for dam construction an option worth considering in design.

Exploitation of the Ujina ore body is estimated to take only between 6 and 7 years to complete, at which time exploitation of the Rosario-Huinquitipa ore body will begin. The Rosario-Huinquitipa ore body is located approximately 25 km from the tailings dam. The increased distance makes the use of waste rock for dam construction economically unattractive.

The tailings produced from both ore bodies are expected to have similar physical characteristics. In particular, their grain size characteristics indicate both are suitable for cycloning to produce sufficient quantities of sand for dam construction.

Neither of these materials sources were available for starter dam construction. Therefore, starter dam construction was completed using local sand and gravel from sources immediately adjacent to the dam site.

Optimization Studies

Dam Alignment Optimization

Following completion of Interim Engineering, the identification of additional ore reserves increased the ultimate storage capacity requirement to 1.8 Billion metric tonnes of tailings. To accommodate this increase, CMDIC identified a Base Case dam alignment that was to be optimized during final design engineering against a set of twelve (12) evaluation criteria.

- Total cost
- Starter dam volume
- Tailings pumping requirements
- Dam foundation conditions
- Investigation requirements
- Saddle dam requirements
- Storage ratio at ultimate dam height
- Infrastructure interference
- Diversion requirements
- Volcanic hazards
- Final tailings surface area
- Potential for additional storage

The alignment optimization study was completed in two phases. An evaluation matrix was developed that qualitatively ranked preference levels (i.e. high, moderate and low) for each of the alternative dam alignments against the evaluation criteria. For criteria
requiring quantitative assessments, comparative cost estimates were completed and the highest cost alternative was assigned the lowest preference level.

The first phase looked at six alignment alternatives, progressively downstream from the Base Case alignment at 500m intervals. The evaluation indicated that total costs were reduced for the downstream alignments as a result of decreasing starter dam and final dam (including saddle dams) volumes and pumping requirements. The downstream alignments also offered greater potential for increased storage capacity, if required. However all of the alternatives presented some degree of interference with existing or planned infrastructure in particular, a proposed railway corridor and an existing water supply well field. The well field was owned and operated by a neighboring mine and thus this interference was a potential “fatal flaw”. Therefore, it was decided that further evaluation was required to determine a preferred dam alignment.

The second phase considered five of the original alignment alternatives, including the Base Case, modified to minimize the potential for this interference. The evaluation confirmed the benefit associated with moving the alignment downstream. All of the alternatives, including the preferred alternative, still had some impact on the existing water supply well field.

To determine the viability of the preferred alternative, an Order of Magnitude Estimate (OME) of the initial capital and total Net Present Value (NPV) development costs was completed for both the Base Case and the preferred dam alignments. The OMEs confirmed significant potential cost savings for the preferred and provided CMDIC with a framework to negotiate for the rights to the existing well field.

**Dam Construction Materials Optimization**

The preferred dam cross section identified during Interim Engineering consisted of a compacted sand and gravel (borrow material) starter dam followed by raising to the ultimate dam height with compacted, cycloned sand tailings. The use of waste rock for dam raising was initially rejected because of perceived limitations on the use of mine trucks for haul distances in excess of 5 km.

In subsequent consultation with CMDIC these limitations were removed and unit costs for waste rock placement costs were updated. The unit rates associated with using dedicated mine equipment for waste rock placement were then compared to unit rates provided by contractors. The comparison confirmed that the use of contractors would be uneconomical (US$2.05/t to US$4.20/t compared to US$0.80/t using mine equipment). The use of contractors also had the potential for complicating the mining operations within the open pit. As a result, that alternative was eliminated from further study.

In addition to the alternatives of raising the dam entirely with waste rock or entirely with tailings sand, a third alternative was considered. This alternative consists of a hybrid dam cross section consisting of a granular borrow starter dam, followed by initial dam raising (first 6 to 7 years) with waste rock, followed by raising to full height with compacted cycloned sand tailings.

As indicated in Table 3 below, the initial capital cost of raising the dam with waste rock is about 33% less than for the tailings sand alternative. However, the NPV operating and deferred capital costs of waste rock placement using mine equipment are higher than those estimated for the tailings sand alternative. On an overall NPV cost basis, the two alternatives were found to have similar estimated costs.
TABLE 3: NET PRESENT VALUE COSTS (1996 US$ x 1,000,000)

<table>
<thead>
<tr>
<th>Dam Cross Section Alternative</th>
<th>Tailings Sand</th>
<th>Waste Rock</th>
<th>Hybrid Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Capital Cost</td>
<td>49.2</td>
<td>32.6</td>
<td>33.1</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>29.4</td>
<td>38.4</td>
<td>31.1</td>
</tr>
<tr>
<td>Deferred Capital Cost</td>
<td>0.4</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>TOTAL NPV COST</td>
<td>79.0</td>
<td>76.8</td>
<td>69.9</td>
</tr>
<tr>
<td>NPV Cost per tonne</td>
<td>US$0.089</td>
<td>US$0.086</td>
<td>US$0.079</td>
</tr>
</tbody>
</table>

A comparison of the NPV costs for the three alternatives indicates a potential cost savings of between 9% and 12% could be realised through the use of the hybrid design over the waste rock and tailings sand dam cross sections, respectively (Figure 2). A sensitivity analysis was completed on the unit rates assumed for hauling waste rock using mine trucks. This analysis indicated that the hybrid cross section remained favored over the tailings sand alternative even if the actual unit rates for waste rock haulage are 2.5 times the rate assumed in the analysis.

Further, waste rock placement is operationally less complicated than tailings sand production and placement and provided CMDIC with more flexibility in raising the dam. Waste rock placement can continue beyond the assumed initial period of 6 to 7 years should operating experience and costs indicate this to be favorable. Also, the waste rock can be placed on a “campaign” basis to suit the mining sequence at the open pit, as opposed to the need for continuous placement required for the tailings sand dam. Therefore, it was concluded that the hybrid section was the preferred alternative.

![Fig. 2: COLLAHUASI TAILINGS DAM – TYPICAL CROSS SECTION](image)

**Dam Construction To Date**

The waste rock dam, which was constructed immediately after the starter dam, and the general operation of the impoundment was entrusted to ORSA (a CMDIC contractor).
After three years of operations, the facilities have operated adequately and without any major problem; only minor modifications of the facilities required to adapt them to real life conditions were done. These mainly consisted in some modifications to the "piping", drop boxes, valves, and water reclaim barge.

Considering that the construction material, which in this case is the mine's waste rock, there is no doubt that the greatest operational problem, to name it such, that has existed during the development of activities has been the lack of uniformity in the dispatch rate of material from the mine. Because of this reason, there have been times when there was idle construction equipment due to the low rate of waste rock available and other moments when the equipment has been unable to place the large quantity of material available. On the other hand, the dispatch of material on average has been less than expected due to problems of availability of large capacity trucks, which are used preferably to transport mineral to the process plant. This has derived in a delay in the dam construction program with respect to the original schedule. Nevertheless, a safety problem, such as could be the excessive reduction in freeboard, has not happened due to this reason mainly because the placement of material has been focused in those areas that needed it the most.

The waste rock material from the mine has been placed in layers approximately 2 m thick and also in thicker lifts in some occasions; this material is placed on the dam by large capacity trucks (220 a 270 short tons) and is later spread by Bulldozers to achieve the required thickness. No additional compaction effort has been used in addition to that provided by the construction equipment (trucks and tractors). The waste material has been characterized by its great diversity in particle size, which has varied from sand with some fines to large rocks with a diameter larger than 1 m. The geologic origin of the material has corresponded to ignimbrite and riolite, with these later ones presenting smaller maximum sizes and better construction characteristics. In fact, they have been used for the top layer of the mine trucks haul roads.

Due to the large size of the particles of the dam construction material, the in-place density has been determined by indirect means: surveying the volume of waste rock placed and controlling the placed tonnage (informed by the mine's dispatch). The measured density has been of 1.9 t/m³, which is close to the 2 t/m³ assumed in the design stage.

**Future Dam Raising Alternatives**

The dam growth rate and, therefore, the material and geometry of each stage of the dam, depends on the following factors:

i. Tailings characteristics (grain size)
ii. Need to defer the major investments associated with the sand dam construction
iii. Improvement in water reclaim
iv. Lengthening the exploitation of the Ujina mine, and
v. Changes in the relative cost structure of dam construction materials.
vi. Availability of waste rock transport equipment
A finer grinding of the mineral generates a lesser content of sand in the tailings, determining in some cases the use of growth methods for dams with smaller cross-sections: centerline method instead of downstream method. The available data for grain size show that the current tailings is finer than the one considered at the start of the project, which indicates that it is necessary to keep in mind the centerline growth option method, which cannot be discarded.

In Chile, the traditional way of raising the sand dams has been through hydraulic discharge from the dam's crest, achieving a natural slope in the order of 4 horizontal to 1 vertical (4H:1V). This type of discharge yields a dam with a larger volume than the paddock system, which allows for a steeper downstream slope and, therefore, less volume. On the other hand, the discharge from the dam's crest has the advantage of achieving a continuous growth while the paddock system's growth is discontinuous requiring a greater sand production initially or a higher and more costly starter dam. The analysis performed indicate that the associated costs (investment, deferred, and operational) are of the same order of magnitude for these two methods of sand placement, reason why they cannot be discarded as options.

Any method that reduces the production of sand means a greater quantity of tailings to be deposited. It is feasible to thicken this tailings with state-of-the-art thickeners allowing for a greater water reclaim. This aspect, due to its environmental impact (reduction in the fresh water demand) and its reduced costs, may be decisive at the moment of decision-making.

The decision to use tailings sand for the dam construction is based on its lower cost as compared to the alternative of using waste rock. A relative change in the cost structure of these materials can make continuing the construction with waste rock competitive as well as prolong the exploitation of the Ujina open pit. If this were to occur, the dam construction would be accomplished with waste rock material, in discreet stages, following a construction method to be selected between centerline and downstream construction methods.

The modification of the tailings deposition scheme in the impoundment (discharge points and location of pond) impacts the height of the dams but should not condition the method of construction as much as the choice of materials.

**Concluding Remarks**

- The definition of the dam's cross-section is strongly influenced by the materials available.
- The presence of waste material at a short distance of the impoundment during the first years of operations makes it possible to construct the dam with this material. Once the mine exploitation is moved to Rosario (farther away), this option stops being attractive from an economic perspective.
• The fine characteristics of the tailings and the convenience of maximizing water reclaim favor the adoption of a centerline construction method and/or the application of the paddock method (allowing for a steeper downstream slope).

• The selection of the geometry and materials for the dam must always be the consequence of a comprehensive analysis of all the factors involved: economic, environmental and operational.

The authors wish to thank and acknowledge the support of Mr. Marcos Pinto, Tailings Dam Operation Supervisor – Collahuasi Mine – Chile, in the preparation of this paper.

References
