The Quillayes sand tailings dam in Chile design and operation

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ABSTRACT
The Quillayes sand tailings dam of Los Pelambres mine, a company owned by Antofagasta Minerals, is currently the highest sand tailings dam in Chile. The dam reached its final height of 198 m in 2008 after 10 years of construction and operation. Early production at the Quillayes deposit was 114,000 tons of copper ore per day, and increased until finally reaching a production level of 140,000 tons in 2008. Existing topographical conditions provided a relatively low reservoir – dam ratio of 3:1. Therefore, a 70m-high starter embankment dam was needed, as well as high yearly increases in height of the dam during the first years. Most of the time, this required the total production of tailings be cycloned in order to produce the required dam raise sand volumes.

During the design stage - originally envisaged for a maximum dam height of 175m - it was possible to test samples of sands obtained from the El Chinche tailings dam that was previously operated at the mine and designed for a much lower mine production level. This allowed for an extensive material testing program on the tailings sands, which included triaxial tests under high confining stresses, considering different densities and fines contents.

The success of the Quillayes tailings dam formed the basis for the design and operation of the present tailings dam at the El Mauro mine, which has a tailings sand dam that will have a final height of 237m.

This paper presents design considerations for the Quillayes tailings deposit, the water diversion scheme, and the sand tailings dam. Main construction and operational aspects as well as post-operational issues applicable to the deposit and tailings dam are also discussed.

Keywords: sand tailings dam, dam construction and operation

1. INTRODUCTION
The Quillayes tailings impoundment of Los Pelambres mine started its operation in 1999. The deposit is located in a seismic area of geological and topographical complexity with a snow-rain watershed of 243.5 km² that made necessary a relatively high rate of the raising of the sand tailings dam during the first two years of operation. Hydrological conditions, as well as the relatively narrow V-shaped valley where the sand dam was located, presented a significant challenge in the design of a sand dam, initially designed for a height of 175 m.

Because of the particular topographic conditions, the cycloning of the total produced tailings was required in order to provide the quantity and quality of sand required for the construction since the sand dam had to grow at a very high rate during the first years. Actually, the dam needed to be raised 37 m over the crest elevation of the starter dam in the first year. During the first years, it was required to place, distribute and compact over one million cubic meters of sand per month.

2. TAILINGS DEPOSIT AND DAM DESIGN
The Quillayes Tailings Storage Facility (TSF) is of special interest, due to a series of conditions that translated into severe design, construction, and operating restrictions. The Los Pelambres mine expansion project is located 300 km north of Santiago at an elevation of more than 1,400 masl, with
the TSF located near the other mine facilities. The operation of the TSF started with a planned maximum capacity of 257 million tons of dry tailings, but a final capacity of 360 million tons was achieved with the final height of 198 m of the tailings sand dam.

2.1 TSF Site Characteristics

The site is located in the foothills of the Andes Mountains, at an average elevation of 1,400 masl, distant some 85 km from the Pacific Ocean (Figure 1). It is situated next to the Cuncumén River valley, a tributary of the Choapa River, approximately 4 km downstream from the confluence of the Piuquenes, Pelambres, and Chacay streams.

![Figure 1](image-url)

**Figure 1.** The Quillayes Tailings Deposit Location.

The hydrological basin has a total watershed area of 243.5 km², with the Los Pelambres River Basin (where the TSF is located) contributing 55% to the total basin. The typical gradient of the contributing basin is 18%, and the gradient of the valley bottom is 8% in the area of the tailings deposit.

The climate of the area is a cold mountain steppe climate, with average temperatures of 10.7 C during the summer and 2.5 C in winter. Average rainfall increases with altitude, as well as solid precipitation, and is concentrated in the months of May and August, which account for more than 80% of total precipitation. Average depth values of the snow cover and its equivalent in water for a 3,000 masl elevation were estimated at 1.5 m and 400 mm, respectively.

The dam foundation consists of fluvial deposits in the central area of the dam, colluvial deposits, and/or alluvial terraced deposits in the left abutment and intrusive rock (granodiorite type) in the right abutment, as presented in Figure 2.
2.2 Tailings Sand Characterization

The dam was constructed by hydraulic deposition of sands obtained from the cycloning of the produced tailings. The typical range of particle size distribution of the copper tailings, sands, and slimes resulting from the cycloning process are shown on Figure 3a. The cyclone station at Quillayes had a production capacity of 1,169 tons per hour (nominal) of sand with 65% concentration of solids by weight, and consisted of two batteries operating in parallel, each of which in turn consisted of 22 cyclones, as shown in Figure 3b.

Most of the engineering effort during the design stage for the original 175 m-high sand dam was focused on determination of the main geotechnical characteristics, both static and dynamic, of the sand to be used in the dam. The sand samples used in all laboratory tests were obtained from the Chinche tailings dam, located only 500 m from the site of the present the Quillayes dam. The Chinche was the tailings deposit used by Los Pelambres mine before 1998, when the original mine was processing approximately 5,000 tons of copper ore per day. The sands of the Chinche were obtained by cycloning the tailings that came from the same ore body that would feed Quillayes. The index properties of the sand are shown in Table 1.
Table 1. Index Properties of Tailings Sands.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Quillayes sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max size</td>
<td>mm</td>
<td>0.6-0.7</td>
</tr>
<tr>
<td>D_{50}</td>
<td>mm</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>D_{10}</td>
<td>mm</td>
<td>0.06-0.04</td>
</tr>
<tr>
<td>C_u</td>
<td></td>
<td>5 to 7</td>
</tr>
<tr>
<td>C_c</td>
<td></td>
<td>1.2 to 1.6</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td>2.67 to 2.70</td>
</tr>
<tr>
<td>( \gamma_{\text{max}} )</td>
<td>t/m³</td>
<td>1.77-1.79</td>
</tr>
<tr>
<td>( \gamma_{\text{min}} )</td>
<td>t/m³</td>
<td>1.28-1.31</td>
</tr>
<tr>
<td>( \gamma_{\text{d Standard Proctor}} )</td>
<td>t/m³</td>
<td>1.60-1.65</td>
</tr>
<tr>
<td>Permeability*</td>
<td>cm/s</td>
<td>1x10^{-3} to 1x10^{-4}</td>
</tr>
<tr>
<td>Fines(200mesh)</td>
<td>%</td>
<td>12-16</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>%</td>
<td>22-23</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>%</td>
<td>NP</td>
</tr>
<tr>
<td>USCS Classification</td>
<td></td>
<td>SM</td>
</tr>
</tbody>
</table>

* Permeability varies from about 1x10^{-4} for 25% of fines to about 5x10^{-4} cm/s for 15% of fines (Barrera & Lara, 1998).

Consolidated isotropically undrained (CIU) triaxial test on 2" samples prepared to a density of 1.50 t/m³ were carried out on tailings sand, the results being shown in Figure 4. The tests were performed at a controlled deformation velocity of 0.3 mm/min, minimum axial deformations of 20% and effective confining stresses of 0.1; 0.2; 0.4; 0.8; 1.6 and 2.4 MPa in order to cover the stress range that would be present in the dam. From these tests, an average internal friction angle of 35° was adopted in the analysis with nil cohesion.

Figure 4. Stress-strain curve and stress paths of tailings sand.

Cyclic shear triaxial tests with controlled stresses were carried out to evaluate liquefaction potential of the tailings sands, using 2" samples of sand from the Chinche dam, prepared by wet compaction (7 to
8%) to a density of 1.50 t/m\(^3\). Confining stresses of 0.2; 0.4 and 0.8 MPa were applied, as well as a cyclic stress ratio of 0.05 to 0.23 at a frequency of 0.1 to 2 Hz.

Curve A and G in Figure 5 show the cyclic strength of tailings sand from El Chinche dam with different fines content for different numbers of cycles of applied load. Curves B to E represent the same type of relationship for other tailings sands with high quartz content as reported by Verdugo (1983) with \(\phi'_3 \leq 0.1\) MPa. Curve F shows a reinterpretation of this relationship for Talabre tailings sand, as reported by Obilinovic & Barrera (1982) with \(\phi'_3\leq0.2\) MPa. A general conclusion is that for the confined pressure tested (\(\phi'_3<0.8\) MPa), all the tailings sands present similar patterns, showing a reduction of cyclic shear strength with increase in the number of cycles, up to 100 cycles. In addition, the cyclic shear strength significantly increases with reduction of the fines content.

![Figure 5: Cyclic Resistance Ratio vs Number of Cycles in different tailing sand.](image)

2.3 Dams

The main dam is a tailings sand dam originally designed to have a maximum height of 175 m after 7 years of operation. The starter dam was a 70 m-high compacted earth embankment (crest elevation 1,333 masl). The starter dam has a volume of 1.7 Mm\(^3\), a crest width of 8 m, and slopes of 1: 2 (V:H). The upstream slope has a maximum soil cover size of 3/8", which acts as a filter and serves as support for the impervious membrane. The downstream slope has a gradient of 1: 1.8 (V:H) above elevation 1,293 masl and 1:4 (V:H) under this elevation, in order to facilitate placement of sand during the initial stage of dam construction. The main role of the impervious membrane was to protect the upstream dam slope from water seepage coming from eventual and temporary increase in water elevation due to flooding.

The hydraulic deposition of sand started filling the wedge downstream of the starter dam until reaching the crest of this dam at elevation 1,333 masl. From that elevation, the dam was raised following the downstream construction method, through continuous hydraulic deposition of tailings sands containing no more than 18% fines (material passing ASTM 200 mesh). The inclined deposition surfaces were compacted by tandem bulldozers and smooth vibratory rollers, with 1: 3.5 (V:H) to 1:4 (V:H) downstream slopes, following what is now generally recognized as the Chilean practice on tailings dams (Valenzuela & Barrera, 1995; Valenzuela, 1996). The cross-section of the dam is shown in Figure 6 and Figure 7 shows a plan view of the dam and its main associated works.
2.4 Dam Stability

One of the main design features is related to the relatively high permeability of sands given by the low percentage of fines (less than 18%) specified, which guarantees a rapid drainage of the sand dam during construction and operation. In this way the potential deformations due to the action of strong earthquakes is limited to relatively minor surface deformations that do not affect the overall dam stability. Another important design feature corresponded to the design of basal drains under the downstream portion of the dam, to take care of the seeping water. These two design features made it possible to obtain a low phreatic surface within the dam, as confirmed later by piezometric readings taken from installed instrumentation.

Static stability analysis using limit equilibrium methods and drained shear strength parameters for initial static analysis and undrained strength parameters for post-seismic analysis resulted in factors of safety of 2.57 and 1.0, respectively. Pseudo-static analysis with undrained shear strength parameters and a seismic coefficient of 0.15 resulted in a factor of safety 1.34 for abandonment stage.

Estimates of dam deformations under seismic loads were carried out using different methods. The pseudo-dynamic analysis proposed by Makdisi and Seed (1978), together with site seismic response spectrum for Ms = 8.3 design earthquake were used and the preliminary estimate of deformations gave a maximum horizontal deformation of 2.60 m in dam crest. Numerical analysis (FLAC$^2$D; Valenzuela & Barrera, 2003) showed deformations of the same order but located near the toe of the dam, corresponding to a possible shallow laminar slip surface. Considering that the V shape of the site where the dam was built could have some influence on the actual behavior of the dam an analysis FLAC$^3$D
Dynamic Stability Analysis

With the described design features, there was no practical concern on either static or seismic stability of such a dam, a consideration that was confirmed by the results of the stability analysis just described. Nevertheless, there were some factors considered unique for this dam, mainly: the high raising rate of 37 m the first year and more than 20 m the following year, the relatively narrow valley where the dam had to be built, and it being the highest of its type in the country. These factors supported the decision to carry out a dynamic stability analysis of the tailings dam, using the finite differences FLAC code. The model for this dynamic stability analysis considered an elastic-perfectly plastic stress strain relationship with a Mohr-Coulomb failure criterion, including the estimate of increments in pore water pressure according to Martin et al (1975). The parameters that influenced the increments in pore water pressure were determined from cyclic triaxial tests and calibrated using axial-symmetric two-dimensional numerical models.

Seepage calculations showed that the phreatic surface would not be over 4 m above the foundation level. Nevertheless, a conservative assumption locating the phreatic surface at 10 m above the level of basal drains was adopted as the initial situation, before the earthquake load was applied.

As already mentioned, in order to consider the effect of the geometry of the narrow valley, a 3D model was used to complement results of the 2D analysis (Valenzuela & Barrera, 2003). The analyses were carried out for a total height of 180 m. The main results of this dynamic stability analysis were:

- Maximum horizontal deformation in the order of 2.85 m near the toe of the dam (2D analysis), in the direction of the slope. This result is quite similar to the 2.60 m estimated using the Makdisi & Seed (1978) approach. The 3D analysis showed deformations at the crest lower than 0.5 m (Lara et al, 1999).
- Potential liquefaction within the dam is restricted to small zones near the toe of the dam. Excess pore water pressure in this area does not exceed 50% of effective confining pressure.
- The impact on the dam behavior of the geometry of the narrow valley on dam behavior is reflected only in slightly larger deformation at the toe of the dam, when comparing 2D and 3D results.
- The higher accelerations occur at the crest of the dam: 0.6 g. An acceleration of 0.37 g was considered at the foundation level.

Alarcon & Barrera (2003) as well as Valenzuela & Barrera (2003) discuss additional specific details of the seismic and static stability analysis carried out during the design stage.

Surface Water Management

The surface water management required of different works was to intercept and divert water floods reaching the deposit area. As already mentioned, the confluence of three creeks is located upstream of the deposit: Piuquenes Creek, Pelambres River, and Chacay Creek, all of which flow into the Cuncumén River. An embankment dam (referred to as “Tail Dam”) intercepting the course of the Cuncumén River was constructed in order to divert this water flow, delivering it into a diversion tunnel.
by means of a spillway, which in turn returns that water to its natural course in a gully located downstream from the toe of the sand dam.

The tail dam is an earth embankment with a maximum height of 40 m, an eight m-wide crest, and 1:2 (V:H) slopes. A 7 to 15 m-deep cut-off trench was excavated at the base of the dam in order to intercept seepage along the bottom of the valley. On the left side of the dam, an emergency spillway diverts excess flow from the tailings deposit.

The tunnel, with a clear width of 5.45 m and a length of approximately 6.0 km, was designed to convey a flow of slightly more than 400 m$^3$/s (1,000-year return period).

In addition, the deposit is equipped with a safety spillway with sufficient capacity to evacuate floods entering the dam basin and making contact with the sand dam. The spillway is located upstream from the sand dam, on the right slope, and consists of a series of catchment gutters, which were constructed as the deposit grew. These evacuating gutters discharge into a duct that continues as a canal, finally discharging downstream of the sand dam into a gully.

2.7 Water Recovery

Water recovery was an important element to be considered during the dam design stage, because water scarcity in the region. Topographic characteristics of the area favored the recovery of water. As Cuncumén River valley is rather narrow (100 to 150 m) and has steep slopes. Therefore, the deposit resulted as quite deep but with a reduced surface, thus favoring relatively low water losses due to evaporation from the wet beach and from the clarification pond. In addition, hydro-geological characteristics of the area indicated that underground discharges would only occur along the bottom of the valley, within a single seepage control section. Although the bottom of the valley contains colluvial material of medium permeability, the impermeable basal rock was located at a shallow depth, which made it possible to recover seepage water by means of a cut-off trench and a grout curtain built downstream of the dam.

The water recovery system consisted of three elevated stations arranged in a hydraulic series, each with its own characteristics. The first was a floating barge 14m long and 7m wide, equipped with six vertical-axis centrifugal pumps. The second station was a mobile re-elevating station equipped with six vertical-axis centrifugal pumps, which needed to be moved as the clear water level rose. The third station was fixed and it consisted of two independent sets of elevating equipment made up of five pumps each.

The sand dam is complemented by a drainage system designed to recover surplus water from the sands deposition and from seepage occurring through the dam and its foundation. This drainage system consists of two longitudinal drains located at the bottom and on both sides of the valley, in addition to spaced side drains on both slopes and taking advantage of existing gullies. The longitudinal drains are inter-connected through drainage fingers installed every 15 m. The slope drains discharge into the longitudinal drains, which in turn deliver water to a seepage pond located downstream from the dam. Each drain consists of highly permeable gravel protected with geotextile in the lower portion and covered with a sand filter on the upper portion.

3. DAM CONSTRUCTION AND OPERATION

3.1 Starter dam construction

Construction of the 70 m-high starter embankment dam and of the basal drains of the main sand dam was completed in 1999. The main findings during construction of these works were:

- Open long fractures in the rock outcroppings that formed part of the left abutment of the dam were identified. These fractures were treated with extensive concrete infilling and dental concrete. In the starter dam area where water could be in direct contact with the abutment
before the tailings slimes would push it back in the deposit, concrete grouting was also carried out.

- During the construction of the 70 m-high starter dam most of the alluvial foundation soils were removed, leaving only some minor sectors with 3 to 5 m of very dense alluvial clayey gravels. In the foundation of the sand dam, these alluvial clayey gravel soils less than 5 m in thickness are also quite dense.

![Figure 8. Starter dam just built](image)

3.2 Beginning of operation

Operation and construction of the sand dam by hydraulic deposition began once construction of the starter dam as well as of all the other facilities necessary to begin operation of the tailings deposit was completed. Operation of the deposit and construction of the sand dam was managed by a fully dedicated management team from the mining company, supported by another company specializing in the operation of this type of facility. The specialized support contract lasted from the beginning of the tailings sand production in November 1999 until 2007, one year prior to the end of the Quillayes operation.

3.3 Main Tasks and Responsibilities of the Operating Company

The main responsibility of the operating company was the production of sand through the cycloning of tailings. Additional responsibilities of the operating company were: the transport, placement and compaction of the sand in the dam, staged installation of the impervious synthetic membrane in the upstream slope, installation of the control instrumentation (i.e. piezometers), support for water recovery pumping maintenance, survey control of dam construction and additional works related to drains, drainage control, and other similar complementary tasks.

The main work of the operating company, both in terms of volume and critical responsibility, was related to sand production and dam construction. The operator had to fulfil strict specifications in terms of sand quality (percentage of fines), compaction degree of the deposited sand and minimum dam freeboard with respect to the level of deposited tailings. The operator was also responsible to avoid any spill that could contaminate the water downstream of the dam.

The beginning of the operation of the tailings sand dam presented some difficulties, mainly due to the grain size distributions contained in the tailings during the start-up of the flotation plant and due to the availability of only one of the two planned cycloning stations for a period of almost six months. These two factors reduced the capacity of sand production and caused initial problems with sand transport.
and sand distribution systems that impacted the dam growth rate. The need of dilution of sand slurries at this early stage in order to compensate for the unforeseen grain size distribution resulted in some difficulties in forming the initial downstream slope, which tended to be flatter than the 1:4 (V:H) specified in the design.

After a few months, when the flotation plant stabilized its production and after optimizations of the cyclone’s operation and of the sand distribution systems, the operation of the dam reached its “normal” operational level that ended up to be much better than originally assumed for this dam.

About 700,000 m$^3$ of sand were deposited and compacted on an average monthly basis, with a maximum of 1,000,000m$^3$ reached in a couple of months. Figure 9 shows the curve of height increase for the dam. During the first two years, the sand dam and the tailings deposit grew more than 30 and 20 m, respectively. This is about 60 and 40 cm per week, requiring very frequent relocations of the sand distribution system (pipes and wooden pipe racks).

After the sand slurry, with solids content by weight of 70%, was placed on the downstream dam slope in layers of variable thickness, spreading, reshaping, and compaction of the sand was carried out by a D6 bulldozer and 6-ton smooth vibratory rollers travelling along the slope pulled by the dozers. Densities of more than 95% of Standard Proctor density were obtained. These densities were checked systematically and periodically at depths of 90, 60, and 30 cm.

![Figure 8](image)

Figure 8. Height increase curve of the Quillayes tailings dam (Barrera & Valenzuela, 2003).

4. DAM BEHAVIOR

4.1 Investigations in the tailings sand dam during construction

During 2001, the owner, through an external international consultant, carried out a soil investigation in the sand tailings dam in order to evaluate in-situ geotechnical properties of the sand as placed, to determine if they met the pre-construction assumptions, or if stability needed to be re-assessed. At the same time, the data collected would support the selection of design parameters for use in the design of the future El Mauro tailings dam with similar sand.

The field investigation included two rotatory drill holes 52 and 54 m deep, SPT and Shelby sampling of sands; four seismic cone penetrometer (SCPT) boreholes 53-66 m deep; down-hole shear wave surveys; seismic refraction surveys; two geophysical profiles; and three 2-m-deep sampling test pits.

The basic sand properties obtained, as well as those used in the original design, are shown in Table 2. The main conclusions of this investigation as reported by Swaisgood (2002) confirmed a layered embankment without weak zones, the absence of water, and geotechnical properties that met design
assumptions. The conclusion was that the construction methods and general design criteria could also be applied in the El Mauro dam. Table 2 shows a comparison between the basic design parameters of the original design and those recommended for the new tailings dam to be built in the new Mauro tailings deposit.

Table 2. Comparison of Key Geotechnical Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original Design</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Density (%)</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>Friction Angle (°)</td>
<td>35-35.7</td>
<td>35</td>
</tr>
<tr>
<td>CRR (1)</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>Average FC (% below#200)</td>
<td>15%</td>
<td>16%</td>
</tr>
<tr>
<td>Permeability (cm/s)</td>
<td>$10^{-3} - 10^{-4}$</td>
<td>$10^{-3} - 10^{-4}$</td>
</tr>
<tr>
<td>Phreatic level (m)(2)</td>
<td>10</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

(1) Cyclic Resistance Ratio
(2) For dynamic analysis purposes.

4.2 Geotechnical Instrumentation

The geotechnical control and monitoring system used in the Quillayes deposit can be divided into two parts. The first part was control during construction of the sand dam, meaning the tailings sands conveyance and depositing phase. Continued measurements of particle size and compaction of the sands deposited in the sand dam were conducted. Daily grain size distribution controls corroborated good performance of the cyclones. At the same time, daily control of compactness conducted in situ, together with grain size analysis, made it possible to verify the degree of compactness of the deposited sands and ensure behavior of the same in compliance with design conditions. Figure 9 shows the level of compaction achieved in the tailings sand during construction of the dam.

The second part of the system has to do with controlling and monitoring of parameters indicating the condition of the structure at all times. To that end, electric vibrating wire piezometers, Casagrande piezometers, accelerographs in different dam wall locations, subsidence cells and topographic control on dam crest were installed. Daily records of the operating parameters of impulsion pumps and flow meters in the seepage collection system made it possible to evaluate volumes of flow seeping in through the dam. Figure 10 shows records of Casagrande and vibrating wire piezometers located
downstream of the starter dam during a 9-year period. Stability of the records is readily apparent, the phreatic line being in this case significantly lower than the assumed design level.

4.3 Increasing height of the Quillayes Tailings Dam

The original design considered a final maximum dam height of 175 m-high, corresponding to a capacity of 257 million tons of dry tailings and approximately 7 years of operation at an average production rate of 114,000 tons of mineral per day. Based on the good results obtained in the construction of the dam and of the investigation of the Quillayes dam performance, a decision was made by the mining company to increase the capacity of the Quillayes tailings deposit. The deposit would increase to 360 million tons by heightening the dam to a maximum of 198 m, thus deferring the need for a new TSF for approximately 3 years.

In general, the same design criteria were considered. However, the basal drains were modified in order to serve the new production level. Pseudo-static and dynamic analysis confirmed the feasibility of the height increase; nevertheless, additional triaxial tests on sand samples under higher confining stresses were carried out, in order to confirm the adequacy of the proposed design.

5. CLOSURE PROJECT

Tailings placement stopped at the end of 2008. As part of the abandonment works, a phyto-stabilization project is being carried out, which during its first stage consisted of testing the planting of 11 species of plants on 30 hectares, equivalent to approximately 25,000 plants. Behavior of the plant species is currently being evaluated in terms of adaptation to the substrate (development and growth), behavior of the plants in terms of bioaccumulation (analysis of plant tissue), behavior of the substrate (soil analysis), and replacement of dead specimens that did not adapt. An additional 30-hectare planting area is being considered for testing shortly. Figure 11 shows phyto-stabilization project in progress.

![Image of phyto-stabilization project](image-url)
6. FINAL REMARKS

Several lessons can be obtained from the successful experience of the Quillayes tailings sand dam:

- The Chilean practice of downstream sand tailings dams, constructed with hydraulic fill methods using relatively pervious sands obtained through the cycloning of tailings, limiting the fines content has proved to be quite satisfactory and safe. Associated with conservative design of generous basal drains, good foundation conditions or adequate treatment of it, the risk of liquefaction has been kept at a very low level even for very strong earthquakes. Design earthquake has a magnitude Ms = 8.3.

- An experienced and well-trained operations team, supervised by an experienced management team are essential for safely constructing and operating this type of deposit and especially for a sand tailings dam.

- Tailings dams are built and operated during a considerable length of time, thus presenting a clear opportunity to apply the Observational Method in order to improve and to optimize the construction and operation.

- Sufficient instrumentation, both for normal conditions as well for eventual seismic events are of paramount importance. An adequate instrumentation network will allow the full application of the Observational Method, thus allowing for optimizations and corrections during construction and operation as well as after end of operation. Periodic analysis of the collected information has to be carried out by experienced geotechnical engineers.

7. REFERENCES


Valenzuela, L. 1996. Characteristics of Chilean Tailings Dams, Large Dams in Chile. Edited by ICOLD.


Verdugo, R. 1983. Influencia del Porcentaje de Finos en la Resistencia Cíclica de Arenas de Relaves, Civil Engineer Thesis, Catholic University, Chile.