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Sand Tailings Dams: Design, Construction and Operation

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Abstract

The design of sand tailings dams for tailings impoundments in highly seismic regions has been subjected to a long development process with continuous improvement mainly because of the general concern originated by several earthquake induced failures. Two important hydraulic sand fills and sand tailings dam failures in the 1960's (San Fernando dam in California and El Cobre tailings dam in Chile) are the most well-known. The development process continued until it achieved the present situation where recent designs show a reasonably high degree of safety and reliability and also relatively cost effective construction and operational control methods.

As a consequence of the knowledge and experience gained mainly over the last 30 years, it has been possible not only to design but also to construct and to operate sand tailings dams of more than 200 m in height and with rates of production and placement of tailings sand as high as 45,000 tons per day. This achievement is the result of continuous knowledge gained regarding geotechnical behaviour of tailings sands under high confining pressures; hydraulic transport and pumping of sandy slurries; new numerical methods of dynamic stability analysis and the improvement of reliable sand disposal and compaction methods.

This paper provides a summary of the evolution that occurred over the last 30 years in the design of tailings impoundments with sand dams. It also describes the fundamental design concepts, the knowledge gained in the behavior of tailings sands under high confining pressures and dynamic loads. The paper finally identifies areas where it is possible to further improve designs, operation and closure. A large part of the experience and examples presented are related to actual tailings dams located in Chile, where several high and large dams exist or are planned to be built shortly.

Introduction

Once mining went beyond the artisan level, it was necessary to accumulate and to store the tailings instead of discharging them directly to areas close to the plant or to existing rivers or lakes or even the sea. Given that the tailings are managed as a slurry with high water content, its safe accumulation would require the construction of a containment dam. In general the most economical solution for the construction of this dam was to use the coarse fraction of the tailings. With this objective, the tailings were classified with hydrocyclones, which generated two flows: underflow or coarse fraction (sand) and the overflow or fine fraction (slimes). The sand was then placed hydraulically to build the containment dam. Using the upstream method of construction the most economic method since it requires the minimum volume of sand, compared with the central and downstream methods, and was therefore the method most used worldwide. This practice was extended gradually to regions with medium to high seismicity but without significant changes to consider the conditions of the new seismic environment.

The upstream method for the construction of sand tailings dams was generally associated with relatively simple tailings cycloning systems with simple mobile cyclones installed in the crest of the growing dam, with little or no control at all of the quality – percentage of fines for instance – of the sand produced. Compaction of the deposited sand was not the general practice and this practice would have been quite inefficient considering the variable characteristics of the produced sand. The construction and operation of these dams were part of the general operation of the mine and consequently were not recognized as a separate industrial process with its own particular requirements.

In the development of the large copper mines in Chile at the beginning of the 20th century, the same general practice of uncompacted upstream tailings was adopted and this system was still used in many of the large mines until the 1960's. The failure of El Cobre sand tailings dam during the earthquake of March 28, 1965, that caused more than 300 casualties made evident the need to review the construction method of sand tailings dams. This need for an improvement of the design and construction of sand tailings dams was even more evident and urgent because of the increasing size of the mining operations that were producing large amounts of tailings which required storage in a safe and cost effective way. Impoundments with sand tailings dams, being in general the less costly systems, were still the preferred solution, particularly when the dams were of great length.

The following presents (i) a summary of the evolution that occurred particularly in Chile over the last 30 years in the design of tailings impoundments with sand dams; (ii) a description of the fundamental design concepts for this type of structure; (iii) the knowledge gained in the behavior of tailings sands under high confining pressures and dynamic loads; (iv) a look at construction challenges related to large dam embankments; and (iv) the identification of areas where it is possible to further improve designs, operation and closure.

Evolution of Sand Tailings Dams in Chilean Mines

Until the 1960's and especially before 1965, many tailings deposits in Chile used sand tailings dams build according to the upstream method. The design and construction of these types of dams were in general performed with limited analytical considerations. It should be noted that modern soil mechanics was developed mainly between 1936 and 1960 and the understanding of soil liquefaction started in the 1960's. Also up to 1970 there were no national regulations or guidelines for the design and construction of tailings dams. On March 28, 1965, a 7.6 magnitude earthquake occurred in the central part of Chile causing the failure at the El Cobre tailings impoundment and the death of approximately 300 persons when the camp of El Cobre, located immediately downstream of the impoundment, was totally buried (Dobry& Alvarez, 1967).

This catastrophic failure was not the first one to occur in Chile. In 1928, as a consequence of the magnitude 8.0 Talca earthquake, the Barahona Impoundment of the Teniente Mine spilled 4 million tons of tailings and 314,000 cubic meters of water, causing 54 fatal victims (Agüero, 1929).

As a consequence of the impact of the tragedy of El Cobre failure, in 1970 the authorities issued a norm that should regulate the design, construction, and operation of sand tailings dams (Decree No. 86 of the Ministry of Mines titled "Regulations for Construction and Operation of Tailings Impoundments").

Decree No. 86 was a great advance since for the first time definitions, criteria, and requirements that must be complied with for the construction and operation of impoundments were provided. It is worth noting that this decree only dealt with those impoundments whose dam was constructed with the coarse fraction of the tailings, leaving out of the norm those with borrow materials (earth embankment or rock waste dams). Implicitly it was recognized that the impoundments with sand dams presented the greatest risk and possibly were the most common types of dams at that time.

The main contributions of Decree No. 86 may be summarized in the following points:

- The design of dams should follow the laws of soil mechanics
- A minimum construction density is required for the sand
- Saturation of the sand is identified as one of the greatest dangers for stability, requiring a base drainage system, permeable sand, and control of the piezometric levels in the dam.
- The upstream method is prohibited (leaving the option of being approved only by special resolution)
- A minimum factor of safety of 1.20 is established for the pseudo-static analysis that considers a seismic coefficient determined based on the population located downstream of the impoundment and within something called the dangerous distance.
- Management of the tailings pond far from the dam and with an appropriate freeboard

The main merit or contribution of the decree was the identification and recognition of the important role of zones of saturated sand in stability. Consequently, in the norm the majority of the articles are focused on assuring that the water does not reach the dam and, if it does reach it, that the sand and its foundation have the capacity to eliminate it quickly. The simplistic form in which the seismic coefficient is determined and how the dangerous distance is determined have been criticized but, although its calculation was simple and arbitrary, it provided values that in the current perspective were not that far off.

This norm was valid until December 29, 2006 when it was replaced by Supreme Decree No. 248 titled "Regulation for Approval of Design, Construction, Operation, and Closure of Tailings Deposits Projects".

After the El Cobre catastrophe, the first reaction from authorities and the industry was to try to avoid solutions based on tailings sand dams and, in consequence, a trend followed to the use of alternative types of containment dams. In the 1970's, embankment dams of the type used in water reservoirs were adopted.

- Colihues 83 m high earth embankment dam (ICOLD, 1996) of El Teniente mine whose design was started at the beginning of the 1970's,
- El Indio 74 m high earth embankment dam (Cia Minera El Indio, 1985) of Cia Minera El Indio, designed at the end of the 1970's, and
- Los Leones, 160 m high rockfill dam (ICOLD, 1996) of the Andina Mine whose final design started in 1974 (ICOLD, 1996). Note: 266 m was the original ultimate height of the dam but the operation stopped when the dam was at 160 m high (Codelco Chile-Division Andina, 1985).

The cross sections of these dams clearly show the typical zoning of materials with an impermeable core. One remarkable difference with water dam is that the construction in stages did not allow for a central core but one inclined. Figure 1 shows the cross section of the Colihues tailings dam embankment as an example of this type of design.

Nevertheless it should be noted that the vulnerability of sand hydraulic fills to liquefaction was not the only consideration taken in consideration in all these cases. Economic reasons, tailings properties and specific geomorphology conditions also contributed to the selection of the type of dam.

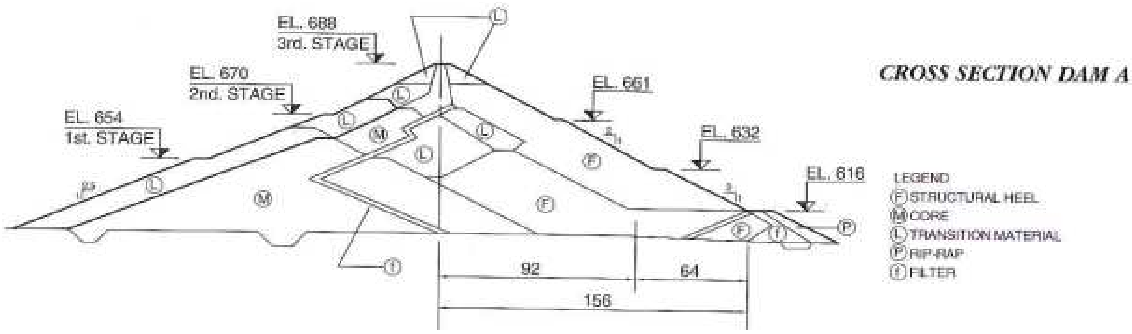

Figure 1 Cross Section of Colihues tailings deposit (dam embankment A)

However, the cost of these types of dams could be too high and the mining industry continued searching for solutions based on the use of tailings sands with improved construction methods, taking advantage of the progress in the knowledge of soil mechanics in the behavior of sands.

The most notable examples are those of El Cobre No. 4 and Pérez Caldera No. 2 tailings impoundments, proposed shortly after the 1965 earthquake. The main features of these dams that represented an improvement to the previous practice of sand tailings dams were: downstream construction method; relatively flat downstream slopes (4 or more to 1; H:V) that allowed the transit of bulldozers for the sand compaction and centralized cyclones stations to guarantee sand quality.

El Cobre No. 4 tailings dam has an upstream slope of 2:1 (H:V) and 4.25:1 (H:V) downstream. The height of the dam reached 65 m in 1993. The features of the dam cross section are shown in Troncoso, 1990.

The Pérez Caldera No. 2 tailings dam had a 2.25:1 (H:V) upstream slope and a 4.0:1 (H:V) downstream slope (Griffin et al, 1973). The operation started in 1979 and the height of the dam reached 118 m in 1992.

In this entire evolutionary process, there is an intermediate case: the dam of the Talabre Impoundment. This design was done at the end of the 1970s and its operation started in 1985. This dam is constructed with tailings sand but has the following particularities: (i) intermediate inclined drain inside the dam; and (ii) downstream slope of 2.5:1 (H:V) as is shown on Figure 2 (ICOLD, 1996). These characteristics led to the construction being done with the paddock method (only one applied in Chile). In addition, due to the high Storage Ratio (SR), the sand transport and placement was done mechanically (instead of the most common hydraulic method).

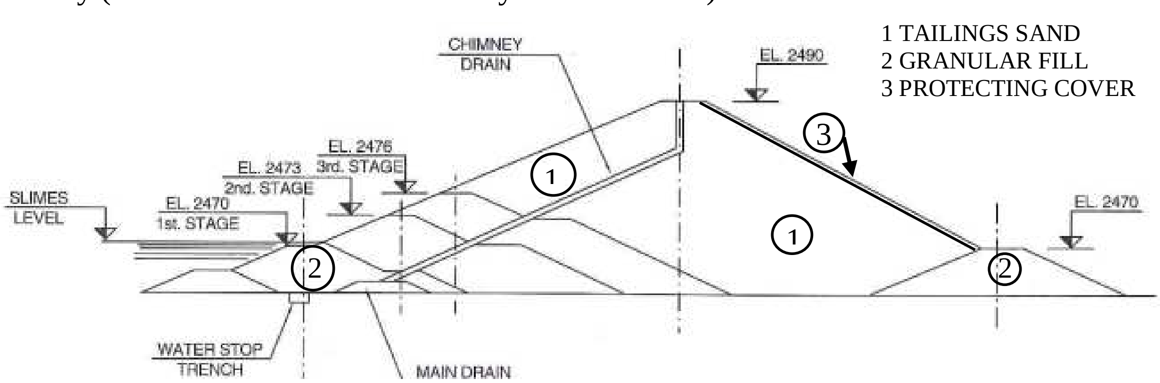

Figure 2 Cross Section of Talabre tailings dam (West dam embankment)

In the middle of the 1990's and after the successful behavior of the sand dams during the earthquake of March, 1985, the design of sand dams faced the challenge of greater heights. The first case corresponds to Quillayes of the Los Pelambres Mine with a 175 m final height. This design summarized all the innovations introduced to that date and included the first studies of the effect of high stress in the behaviour of sands. Also, a 3D dynamic analysis was performed for the first time (Lara et al, 1999; Valenzuela & Barrera, 2003). A few years later, this dam was raised to 198 m to extend the useful life of the impoundment. As a consequence of the limited capacity of the Quillayes Deposit, the Mauro Deposit was selected and designed for continuing the operation of the mine. This impoundment is located 60 km from the plant, with a sand dam with a final maximum height of 248 m, which for the first time went beyond the 200 m barrier in a high seismicity region (Alarcón & Barrera, 2003). Table 1 gives an idea of the increasing height of the tailings dams since the 1970's.

Table 1 – Large tailings dams in Chile

Deposit	Mine	Design Period	Dam Material	Max Final Height (m)	Operation period
El Cobre N°4	El Soldado	? to 1966	Sand	65	1967 to 1993
Colihues	Teniente	1973 to 1975	Borrow	83	1976 to 1986
Perez Caldera N°2	Los Bronces	1973 to 1977	Sand	118	1978 to 1991
Los Leones	Andina	? to 1978	Borrow	160	1980 to 1999
El Indio	El Indio	1973 to 1975	Borrow	74	1981 to 1999
Talabre	Chuquicamata	1973 to 1981	Sand	46	1985 →
Las Tórtolas	Los Bronces	1983 to 1990	Sand	190	1992 →
Torito	El Soldado	1985 to 1991	Sand	125	1993 →
Quillayes	Los Pelambres	1996 to 1998	Sand	198	1999 to 2008
Ovejería	Andina	1989 to 1999	Sand	120	2001 →
Mauro	Los Pelambres	2003 to 2006	Sand	248	2009 →

(*) This table does not include the following tailings dams built with borrow or waste rock like as Caren (1986 - El Teniente); Candelaria (1995) and Pampa Pabellon (1998 - Collahuasi)

Currently, there are designs that are close to 300 m in final height and, from a stability point of view, there are technical tools to assure the stability of these large dams. It all indicates that the greatest challenges in the future will be related to reclaiming a larger part of the water from the tailings, seepage control, minimization of dust emissions,

Key Design Aspects

The design of a sand dam has to respond to the following key aspects:

1. <u>Seismic stability against an extreme event</u>. This means that the dam must maintain the containment function of the deposited tailings even under the worst seismic event. In other words, the dam cannot dump part or all the tailings downstream of the dam in an earthquake.

2. <u>Construction of the dam as part of the operation of the impoundment.</u> The production of sand is a daily task that has to be adjusted to the features of the tailings provided by the flotation plant. This condition does not exist in civil construction where the construction material is selected and processed until the required quality is obtained and then is transported by trucks and placed on the

dam. In this case, the material is classified in the cyclone station, transported by pipe, hydraulically discharged from the dam crest, and then mechanically compacted. All of which present challenges derived from (i) the inherent variability of the tailings (in gradation, solids content and tonnage); (ii) height and length of the dam and (iii) the large volumes to be managed

The seismic stability of a sand dam depends on three factors of a different nature: (i) the intrinsic parameters of the material: density, strength parameters (cohesion and friction angle), and the level of saturation; (ii) characteristics of the seismic forces: content of frequencies, duration of the event, and maximum accelerations; and (iii) geometry of the dam: especially the height of the dam. This last indicates that for given foundations conditions, the response of the dam is variable during operations but constant after closure. Of all the factors mentioned above, the most critical for the stability is the level of saturation of the sand fill since only when the material has over 85% of saturation can the liquefaction phenomenon happen, leading to greater degradation of the strength capacity and large deformations. Therefore, the most important issue to be addressed during design is seepage control through the dam and its foundation, in case of alluvial fine deposits. The design should focus in to guarantee a potential saturated zone as small as possible even under the worst conditions, meaning that the zone should be safely contained, i.e. that stability has to be guaranteed even considering that this reduced saturated zone has liquefied during the earthquake.

The construction of a sand tailings dam involves the following challenges: (i) production of sand with the grain size distribution that complies with the minimum design permeability; (ii) hydraulic transport of the sand to facilitate the designed discharge sequence (iii) producing and placing the required quantity of sand to maintain the minimum freeboard with respect to the tailings/slimes impounded and the geometry of the dam (slopes and crest width); and (iv) compaction of the placed sand to reach the minimum design density. Each one of these aspects has different solutions depending on the project characteristics

Design Evolution and Examples

Permeability and drainage

At the end of the 1960's and beginning of the 1970's it became clear that the main factor for the seismic instability was the saturation of the sands. There were two ways to avoid the destabilizing effects: increase the level of compaction of the sand and, the more obvious, avoid the sand from becoming saturated. It is not the objective of this paper to provide details as to why both ways were valid since both have been technically verified. Actually, in practice both ways were applied, although at the beginning there was not much clarity about what the limits for the geotechnical parameters would be to reduce at a minimum the risk of failure due to liquefaction of the hydraulic sand fill. Obviously one of the key parameters is the permeability of the sand which is closely correlated to the fines content (% passing the #200 sieve) in the sand. The fines content became in practice the main parameter used for quality control of the sand during the construction/operation. The first recommendations led to a maximum fines content of 10% (ref) assuming permeability greater than 1E-3 cm/s, which in theory seemed good. But several problems surfaced:

i) To achieve such a 'coarse' material (maximum 10% of fines), double cycloning was required which constraints significantly the sand production and requires higher consumption of water for dilution. In practical terms, this meant that for each ton of tailings processed in double cyclones not more than 0.25 tons of sand are produced
ii) But there were other problems derived from such a 'coarse' grain size: the deposition slope of the sand on the downstream slope was much steeper than what was required to be able to compact the tailings by passes of compaction equipment,

iii) Another issue was the problem with hydraulic transport of the coarser sand given its strong tendency to sediment even at high weight concentrations

In parallel to the definition of the gradation of the sand, it was necessary to adopt minimum criteria for the drainage system. This system is what allows the water to be drained from the sand quickly and be evacuated to the outside of the dam, thus avoiding saturation. In this way, the permeability of the sand and the drainage system work in series and are key for the stability of the dam.

As indicated above, a restriction of the percentage of fines to values of less than 10% represented an important decrease in the production of sand, which is critical when the impoundment /dam ratio or storage ratio (SR) is less than 3 and the insufficiency of sand to construct the dam must be replaced with borrow material at a much higher cost. This factor and the difficulties mentioned above prompted the study to determine how much more fines the sand could have and still continue to have a drained behavior that would avoid permanent saturation.

The study performed in the mid 1980's concluded that the minimum permeability of the sand in the dam must be greater than 2E-4 cm/s. This value was determined based on the theoretical percolation time of the water in the sand and piezometric measurements of the impoundments in operation. It is worth noting that the correlation of percentage of fines and permeability although still being valid in general provides different values depending on the specific gravity (G) of the tailings or mineral. For example, tailings with G = 2.7 to 2.8 (typical of copper) indicate a fine percentage between 15 and 18% but tailings with G = 3.0 to 3.2 indicate a percentage of fines larger than 20 to 25% (case for iron tailings or copper tailings with high pyrite or magnetite content).

At Las Tortolas tailings dam, being the first important tailings dam designed using modern soil mechanics and soil dynamic concepts and taking in consideration that was the higher tailings dam to be build, additionally in a high seismic area near the main city of Santiago the design adopted a conservative value of 10%, although the laboratory tests and seismic stability analysis showed that the dam would be stable even with sand with 15% of fines. At Las Tortolas, the SR was higher than 7 and, therefore, the sand production rate was not critical.

The studies performed in the 1980's and the 1990's have systematically validated (for porphyric copper tailings) a range for the maximum content of fines between 15 and 18%. The available examples are: Quillayes and Mauro tailings dam of Pelambres mine, heightening of Las Tórtolas of Los Bronces mine, Ovejería dam of Andina mine and Torito dam of the El Soldado mine.

Table 2 – Fines content of tailings in large impoundments of Chile

	Fines content (%)		**D_{50} (µm)**	**Operation period**
	Normal range	**Maximum**	**Avg of Total Tailings**	
Las Tórtolas (2007)	12 – 15	16	70 – 73	(*) 2007 →
Torito	15 – 18	20	70	1993 →
Ovejería	12 – 14	15	85	2001 →
Quillayes	13 – 17	18	75	1999 - 2009
Mauro	13 – 16	18	75	2009 →

(*) The fines content range before 2007 was 10 to 13%,

Effect of height on sands

The continuous increase in the levels of production of the mineral strongly associated with the demand and the low ore grade has led to the design of tailings impoundments with larger capacity and consequently higher dams. In Chile, up until the late 1970's, the majority of the sand tailings dams were not higher than 70 m. The Pérez Caldera No. 2 tailings dam is the first one designed for a final height of 118 m, that is significantly higher than the previous cases existing in Chile. In 1984, the dam for the Las Tortolas Impoundment was designed to reach a final height of 150 m. Since this was a height without precedents in a highly seismic zone, extensive studies were carried out to support the design. The geotechnical characterization of the sand included cyclic triaxial tests carried out in Chile and USA and dynamic analysis was performed for the first time using the finite differences method (DSAGE), precursor of FLAC (Valenzuela & Campaña, 2008).

This tendency for higher tailings dams grew in importance in the 1990's with the Quillayes Impoundment of the Pelambres mine designed for a final height of 175 m and a useful life of eight years. A few years after operations started, a verification of the properties of the sands in the dam was done (Swaisgood, 2002, Valenzuela & Barrera, 2003) through a complete field and laboratory investigation which confirmed the parameters and criteria assumed at the design stage. Based on the above mentioned investigation that confirmed not only the assumed geotechnical parameters but also the adequacy of the construction method and quality control it was possible to provide a solution for an important increase of production, allowing to the raise of the dam to 198 m. In 2004 the basic design of the Mauro impoundment, which would replace Quillayes once its useful life was complete, was carried out. The corresponding tailings dam required a final height of 248 m to store 27 years of operation at a production rate of 175 KTPD of treated ore (Alarcón & Barrera (2003)). Since this case went well beyond the 200 m of previous experience and actually also represented a significant change in the rhythm at which the previous cases of new heights for this type of dams have been cautiously considered (120. 150, 175 and 200 m), an extensive investigation campaign of high stress triaxial tests were performed with the objective of evaluating the strength, deformations and permeability characteristics of tailings sand under maximum vertical stress close to 4.5 MPa.

After 2004,the knowledge of the behavior of tailings sands increases significantly due to new projects of large tailings impoundments and the involvement of two Chilean universities in this effort to characterize the tailings sands behaviour at high confining stress. The analysis of these tests have allowed to differentiate the behavior of tailing sands with that observed of sands in their natural state, as shown in Campaña (2011), with the following main conclusions:

- The permeability coefficient decreases as the confining stress increases, product of the decrease in density and the generation of fines by breaking of particles, although this last effect is relatively a minor one at least for tailings sands with 15 to 21% fines content (see Figure 3).

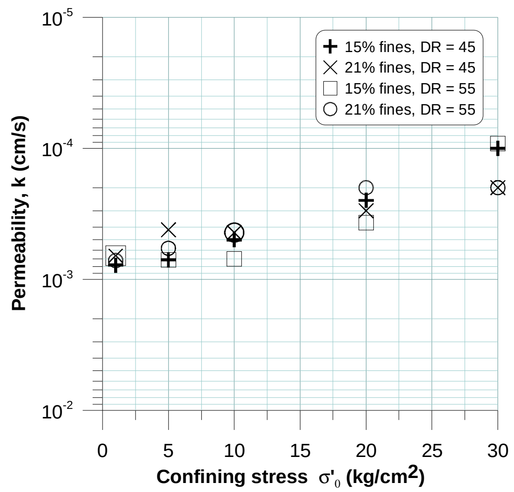

Figure 3 Variation of permeability coefficient versus confining stress for 15 and 21% of fines content (Valenzuela & Campaña, 2008)

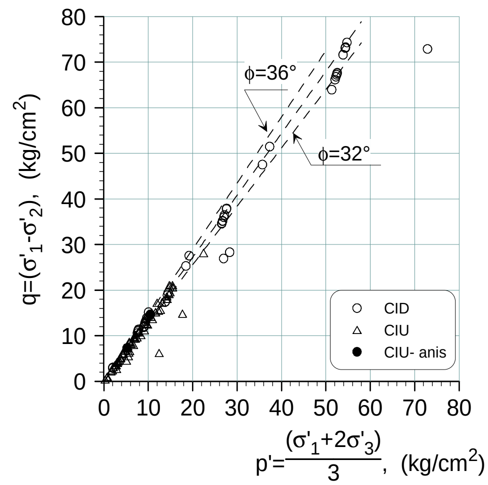

Figure 4 Drained and undrained shear strength envelope in tailings sand with 12 to 30% fines content and R_D between 45 and 85% (Campaña, 2011)

- The breakup of particles is not as pronounced as in some natural sands, in consequence, the drained strength envelope is lineal and not bi-lineal as could be expected. The reason is that particles in tailings sands have already been submitted to extreme conditions in the crushing and milling process of the mine ore, consequently the stronger particles have remained in the coarser fraction of the sands.
- It is also observed that drained strength envelope it is not too much sensitive to variations in the fines content. In fact, for the four tailing sand tested the strength envelope is defined by null cohesion and internal friction angle of 34° (±2°), even when the fines content range are between 12 to 30% (see Figure 4).
- The average undrained resistance decreases when the fines content increases, but are comparatively greater than those reported in the technical literature for natural sands, as may be observed in Figure 5
- For confining stress larger than 1.0Mpa (10 kg/cm^2), there are no significant changes in the cyclic strength (Rc). The application of the typical overburden adjustment factors (Kσ), suggested in the technical literature to evaluate the cyclic strength (Rc) of natural sands under high confining stress may implicate an undervalue of the cyclic strength in tailings sands, as may be seen on Figure 6.

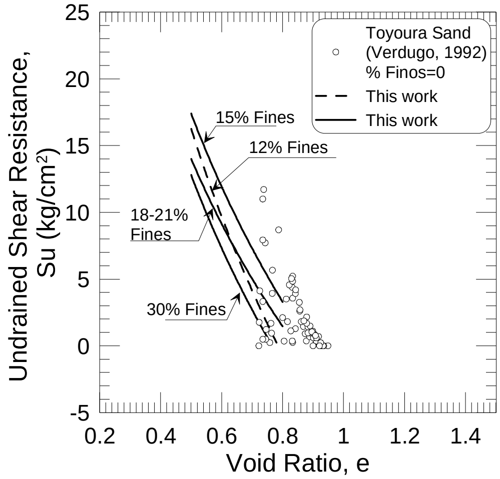

Figure 5 Average variation of undrained strength (Su), voids ratio (e) and fines content. Four types of copper tailings sands (Campaña, 2011)

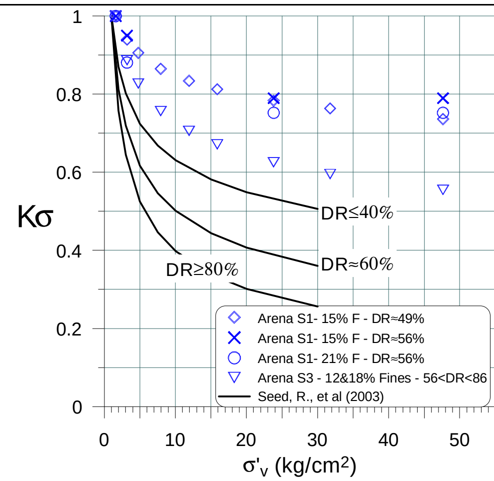

Figure 6 Variation of overburden adjustment factors (Kσ), for tailings sands with 15 to 21% fines content (Campaña, 2011**)**

The above mentioned conclusions result of several studies have been the support to the design of a feature sand tailings dam 300 m high in the south of Peru with copper mineral of the type tested for other sands related to similar copper ore in Chile and Peru, all of them with similar geological origin. Although the conclusions reached with these studies must be reviewed for sands with different geology or mineralogy, it seems to be clear that from the point of view of the geotechnical behavior of tailings sands product of the treatment of copper porphyry ore there is no major restrictions for dams to go higher than 300 m, although of course many other considerations have to be taken in to account for decisions of this nature.

Construction Challenges

The construction of sand dams has had a steady evolution from the operation of isolated cyclones located on the crest of the dam with production capacity of 400 tpd to cyclone stations located at the abutments with production capacity of 40,000 tpd. Together with the production of sand came the sand transport and placement and the slope of the dam, forming a system that required an integral approach.

Sand transport

The large majority of the mining operations at the end of the 1960's did not go beyond 5,000 tpd with some exceptions of up to 20,000 tpd (El Teniente and Chuquicamata Mines). At this level of production, the operation of several independent cyclones located at the crest were enough to produce the quantity of sand and only needed to be relocated periodically with the help of light equipment and seasonal staff. This production scheme had its weaknesses mainly associated to the variability in the sand quality since it was not possible to maintain the constant stress on the cyclones which affected the fines content in the underflow. The requirements derived from DS86 and the sustained increase in the production was the first promoter in the need to group the cyclones in a station. In a station, a much more homogeneous sand was able to be produced but there appeared another problem: the transport of the sand from the station to the dam. This transport was done by pipelines and centrifugal pumps on line when gravity was not enough. At that time, pumps were placed 200 to 300 m apart in order to use pipelines of normal thickness (and not high pressure). This solution of pumps in line operated reasonably well for distances not longer than 600 m (equivalent to two or three pumps in line) but generated big problems in longer distances given that the failure of one pump interrupted the flow and did not allow the flow to reach the end locations. Together with the above, infrastructure was required that would group pipelines, pumps, and power supply, which required maintenance and periodic relocations. The pump stoppages caused also that the sand became concentrated and accumulated near the station and that, on the other hand, the farthest sector had a deficit of this material with the associated ends of the dam not being level. The effect of this was that in the areas of the dam with deficit of sand placed, the freeboard was very low which – when it did not comply with the minimum required for the project – required fills with borrow material at high cost, restricted area, and difficult access. The repetition of this situation led to El Cobre No. 4 Tailings Deposit to replace the centrifugal pumps with positive displacement pumps (PD) in 1988. This innovation represented an unprecedented experience in the management of tailings sands in the world. Two PD pumps of 31 l/s (equivalent to 150 t/hr) were installed. As with all innovations, there were some difficulties but these were solved in the first year of operations and, in fact, the manufacturers used this experience to make adjustment to the pump design. In general, the current design of a sand dam longer than 1.5 km considers central classification stations and positive displacement pumps to transport the sands throughout the dam as is the case of the impoundments El Torito and Ovejería.

Sand discharge

The common method for discharging the sand on the dam is called spigot, consisting in the discharge of sand from the crest of the dam from one or more locations. In the case of a centralized cyclone station, the discharge is done through several locations at the same time. The sand transported to the dam is derived to a pipeline (distribution pipe) that is approximately 200 m long (see Figure 7) that has holes spaced every 3 m. Each orifice has a polyurethane nozzle to resist high velocities. The angle of the nozzle with the horizontal and the diameter of the nozzle are adjusted during operations to obtain an even and homogeneous discharge avoiding focusing the jet and slope erosion or the segregation of the flow of sand. This pipeline with orifices is used during the period that an approximately 30 cm thick sand layer is formed on the slope. The entire system is mounted on a wooden structure of 3 to 4 m of useful height which requires its periodic relocation. This technology – first used at the El Cobre No. 4 Tailings Dam is applied in all the sand dams in Chile of mines with more than 15,000 tpd production and large dams. Similar schemes have been applied outside of Chile and in some cases with centerline growth, the support structure has been replaced with a sophisticated steel structure which uses hydraulic jacks for the periodic raising of the pipelines (Cerro Verde Tailings Impoundment).

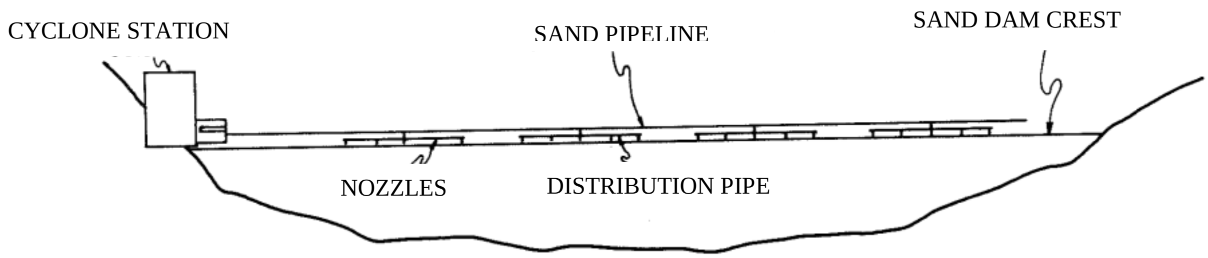

Figure 7 Spigot System to discharge Sand.

Start of construction of a sand dam

The normal placement of sand requires having enough aerial space for a pad where sand is discharging and another pad waiting to be used once the first pad is completed, drained, and compacted (when necessary). The number of pads depends on the permeability of the sand, the production of the sand, and the size of the starter dam. In several cases, the solution to this has been the construction of temporary sand discharge lines located in the downstream area of the starter dam in order to generate additional locations to increase the placement area. In general, the initial phase of construction of a sand dam is a critical period because the cyclone station is also being adjusted and the discharge from the crest must be done very carefully to not damage the downstream slope of the starter dam or generate a segregation than concentrates fines at the base of the dam, affecting the operation of the drainage system and the permeability of the sand.

Experience indicates that in the cases where the growth of the impoundment (tailings/slimes) in the first year of operations will surpass the starter dam by more than 15 m, the sand placement phase is always critical and must be carefully programmed and designed in the project stage.

Further Studies and Improvements

The Chilean practice of sand tailings dams has been very successful but it should be recognized that this practice has been related mainly, at least for the higher dams, to the use of sand from porphyry copper tailings. Evidently the main conclusions commented in this paper regarding the geotechnical characteristics and geotechnical behavior of sands under normal and high confining stresses has to be confirmed for other type of tailings. Also an aspect that it is characteristic of the Chilean environment is the relatively dry climate presents in most of the mine sites and consequently the potential acid generation is not a critical issue, which is not the case in other parts of the world where this aspect should be reviewed carefully.

There is relatively limited experience, at least in Chile, with high dams using the centerline method which should be perfectly feasible but that presents some practical or operational complications that require additional analysis and field trials: installation of impervious membranes in the upstream slope could be cumbersome in cases where water pond can reach the sand dam.

For very large sand tailings dams the control of dust could be an important issue mainly when water is scarce. The use of chemical additives is still a costly solution and it could work against the effort put on the compaction of the sand. Additional investigation is needed in relation with this problem.

Careful monitoring and analysis of the current dams in operation is required to better understand the real needs for compaction effort in the construction. Although the compaction of sand as this is placed in the slope has been considered a prudent procedure the fact is that a relatively small compaction effort is needed to reach a safe relative density in the superficial deposited layer. If compaction proves not to be strictly necessary, even under seismic loads, the downstream slope could be steeper since the current flat slopes where determined mainly to facilitate the work of the compaction equipment.

References

Agüero, G., 1929. Formación de Depósitos de Relaves en el Mineral del Teniente. Anales del Instituto de Ingenieros de Chile, No. 5. 164-187 (in Spanish)

Alarcón, J.C., Barrera, S., 2003. "Dams of Great Height, a Challenge". Symposium of Tailings, ICOLD, Montreal

Barrera, S. & Obilinovic, H., 1982. Dynamic Analysis of the North Talabre Tailings Dams. 1er Congreso Chileno de Ingeniería Geotécnica. SOCHIMSYF. Santiago, Chile. 387–403 (in Spanish)

Barrera, S. & Valenzuela, L. 2003, Construction Evaluation of a Sand Dam of Great Height. Symposium on Major Challenges in Tailings Dams, CIGB-ICOLD, June, Montreal, Canada.

Campaña, J., 2011. Comportamiento de arenas de relave a altas presiones. Thesis of Master's Degree in Engineering Sciences specialized in Geotechnical Engineering, University of Chile (in Spanish)

Cia Minera El Indio, 1985. Tranque El Indio. Primer Taller para Especialistas sobre Tranques de Relave. IIMCH. Santiago, Chile (in Spanish)

Codelco Chile – División Andina, 1985. Proyecto de Disposición de Relaves – Embalse Los Leones". 1^er^ Taller para Especialistas sobre Tranques de Relave. IIMCH. Santiago, Chile (in Spanish)

Dobry, R. & Alvarez. L., 1967. Seismic Failures of Chilean Tailings Dams. Journal of Soil Mechanics and Foundations Divisions. ASCE. V. 93. No. SM6. Proc. Paper SS82

Griffin, P.M., Smith, E.S., Von Loebenstein, J.G. & Edwards, R., 1973. Perez Caldera Tailings Dams – A Case History. Proc. Pan-Am Conf. on Soil Mechanics and Found. Eng. Vancouver, Canada

ICOLD, 1996. Large Dams in Chile. Chilean National Committee on Large Dams. Santiago, Chile.

Lara, J.L., Gómez, P. & Barrera, S., (1999). "Análisis Dinámico Tridimensional de la Presa de Arena de Relaves Quillayes Pelambres-Chile", XI Conf. Panam. de Mec. de Suelos e Ing. Geot., Foz do Iguaçu, Brasil (in Spanish).

Obilinovic, H. & Barrera, S., 1982. Soil Properties of Talabre Tailings Dams. 1^er^ Congreso Chileno de Ingeniería Geotécnica. SOCHIMSYF. Santiago, Chile. 369 - 386 (in Spanish)

Swaisgood, J., 2002. The Investigation and Evaluation of Quiyalles Dam. Technical Visit. High Density & Paste 2002. Santiago, Chile (unpublished)

Troncoso, J., 1990. Seismic Responses of Tailings Dams Built with Cohesionless Soils to Different Types of Ground Motions. Proceedings ICOLD International Symposium on safety and rehabilitation of Tailings dams. Sydney, Australia. 82–89

Troncoso, J., Avendaño, A. & Vergara, A., 1993. The Seismic Failure of Barahona Tailings Dam, 3^rd^ International Conference on case Histories in Geotechnical Engineering. St. Louis. 1473 – 1479

Valenzuela, L. & Barrera, S., 2002. Characteristics of Chilean Tailings Deposits. High Density & Paste Seminar. Santiago, Chile

Valenzuela, L. & Barrera, S., 2003. "Seismic Design of Los Quillayes Tailings Dams in Chile". 12^th^ Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Cambridge, MA

Valenzuela, L. & Campaña, J., 2008. Geotechnical Challenges in the Mining Industry: the Case of High Tailings Dams and Waste Rock Dumps. COBRAMSEG 2008. Buzios, Brasil.