COPPER 2022

November 13 - 17, 2022.

COPPER INTERNATIONAL CONFERENCE

SANTIAGO/CHILE

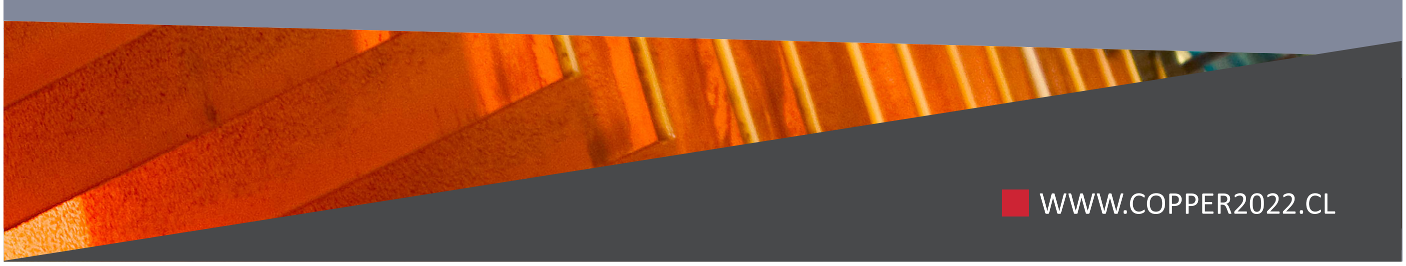
ELEVENTH EDITION OF THE SERIES

Volume 8:

WASTE MANAGEMENT

Edited by:

Instituto de Ingenieros de Minas de Chile (IIMCh)



WWW.COPPER2022.CL

Seismic Performance of Chilean Tailings Sand Dams

Campaña, José, Arcadis, Chile

Verdugo, Ramón, CMGI, Chile

Valenzuela, Luis, Consultant, Chile

Abstract

Chile is known as one of the most seismic countries in the world, being responsible for more than 40% of the seismic energy liberated globally. The Valdivia earthquake (EQ) of 1960 with a magnitude Mw=9.5 is the greater EQ ever registered. More recently in February 2010 occurred the Maule EQ of Mw=8.8 which is the 6^{th} world bigger earthquake. During the last 20 years 15 earthquake of Mw>7.5 has occurred in Chile. The paper presents a summary of the performance of tailing dams in Chile (heights ≥ 15 m). Special attention is given to sand tailings dams that represent good examples of local development in dam engineering. The paper analyses design criteria, local dam safety legislation, dam design and construction practices.

1. Introduction

Formally in Chile there are 112 active tailings deposits mainly distributed in the central and north regions. There are 645 other tailings deposits registered by a government agency including some small operations but mostly inactive and abandoned deposits (SERNAGEOMIN, 2022). Currently, approximately 1,7 Million-ton/day of tailings are generated, and large mining operations represent the main fraction of that production (over 93%), in general including large tailings deposits with some very high dams. These major facilities are designed, built, and operated with best-world standards and in most cases applying the observational method.

The objective of this paper is to share the adequate performance of tailing sand dams as designed in Chile, that have been subjected to very strong earthquakes. In the case of sand tailings dams constructed with the downstream method, there is already a 200 m high dam that ended its operation in 2008 and another one designed for a height of 240 m. The know-how and experience gained with this type of dams have been applied in the design of similar sand dams in Australia, Canada and Perú. In the construction of tailings sand dams, sand can be deposited hydraulically directly on the growing dam slope (spigotting construction) or, alternatively, deposited in cells (paddock construction), see Valenzuela 2015, for more detail. There are three basic types of tailings dams, referred to as upstream, downstream, and centerline, according to their method of growth, as indicated in Figure 1.

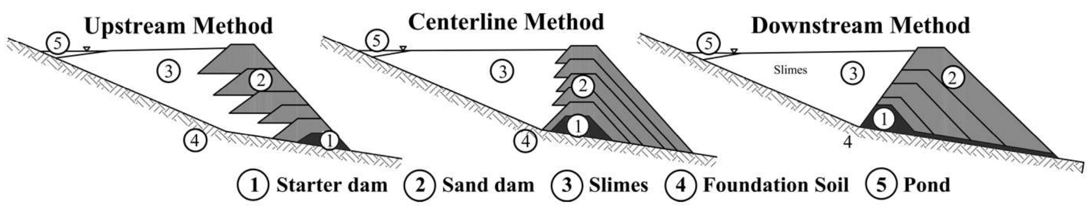


Figure 1: Cross sections of tailings dams according to growth method.

Before the failure of El Cobre dam in 1965 triggered by La Ligua earthquake (Mw=7.4) that provoked more than 200 casualties, most of the tailings dams in Chile were built using the upstream method. This type of construction method was banned in Chile as of 1970 through Decree 86 issued by the Ministry of Mining, unless a specific permit was issued by the national director of the agency for extraordinary conditions. However, it was not until 2007 that Decree 248 confirmed banning of tailings dams constructed using the upstream method with no exception (*Valenzuela & Campaña, 2021*).

2. Tectonic and seismic Chilean environment

Chile is in one of the most active seismic zones in the world, being responsible for more than 40% of the seismic energy liberated globally (Lomnitz, 2004). In Chile, large and destructive earthquakes (EQ) occur frequently, it is estimated that a large earthquake of Mw≥ 8.0 occur every 10 to 20 years while giant mega earthquakes of Mw≥ 8.5 occur at the average rate of two per century (*Ruiz & Madariaga, 2018*) and (*Madariaga, 1998*). In the last century, ten (10) EQ of magnitude greater than Mw 8.0 have struck along the Chilean subduction zone (*Ruiz & Madariaga, 2018*), including the largest magnitude EQ recorded in the instrumental period, the Mw=9.5 Valdivia in 1960. A list of the EQs of magnitude M≥7.5 occurred in Chile since 1850 are summarized in Table 1 and their respective epicentres are plotted in Figure 2. In the case of EQs occurred before 1979, the Richter Magnitude is informed, whereas for those occurred after, the Moment Magnitude Mw is reported. It is observed that the Chilean territory has been continuously struck by strong seismic events, which imply, due to the narrow width of Chilean territory, that all the Chilean dams have been subjected to strong seismic demands.

Figure 2: EQs M ≥ 7.5 since 1850.

Table 1: EQs of M ≥ 7.5 since 1870.

Date	Lat.	Long.	Depth (km)	M
16-09-2015	-31,572	-71,674	22.4	8.3
03-04-2014	-20,570	-70,493	22.4	7.7
01-04-2014	-19,609	-70,769	25	8.2
27-02-2010	-36.122	-72.898	22.9	8.8
14-11-2007	-22.247	-69.890	40	7.7
13-06-2005	-19.987	-69.197	115,	7.8
30-07-1995	-23.340	-70.294	45.6	8.0
05-03-1987	-24.388	-70.161	62.3	7.6
03-03-1985	-33.135	-71.871	33	8.O
10-05-1975	-38.183	-73.232	6	7.7
09-07-1971	-32.601	-71.076	60.3	7.8
28-12-1966	-25.494	-70.550	25	7.7
22-05-1960	-38.143	-73.407	25	9.5
22-05-1960	-38.061	-73.039	25	7.8
21-05-1960	-37.824	-73.353	25	8.1
06-05-1953	-37.093	-72.866	66	7.5
06-04-1943	-31.432	-71.475	35	8.1
25-01-1939	-36.305	-72.315	35	7.8
13-07-1936	-24.720	-70.110	35	7.5
01-12-1928	-35.155	-72.105	35	7.7
11-11-1922	-28.293	-69.852	70	8.5
04-12-1918	-26.538	-70.608	40	7.8
17-08-1906	-32.400	-71.400	35	8.2

3. Tailing Sand Dams

The expression “hydraulic fill” is generally understood to refer to an artificial fill composed of soils that are conveyed and deposited by hydraulic means. Tailings sand dams are a special type of hydraulic fill dam for containment of fine mine waste (tailings). This type of construction dates back to at least the middle of the 19th Century. This has been the most used type of dam in the mining industry, as in many cases it is markedly cheaper than other alternative types, such as compacted earth or rock-fill dams although in some cases the use of waste rock represented also a relatively economic solution if waste rock was available at a short transport distance.

The material used to build tailings sand dams is the sand obtained from treatment of mine tailings themselves. A centrifugal mechanical device called a cyclone separates the tailings into a coarse portion, generically referred to as sand (underflow), and a fine portion, generally referred to as slime (overflow).

4. Behavior of granular soils under high confining pressures

The great height of some dams makes it imperative to assess the impact of high confinement pressures on the behaviour and geotechnical properties of the granular materials that constitute the dam, such as the permeability, compressibility, and shear resistance of the sands (drained and undrained). The compressibility and permeability characteristics of gravel and rock-fill subjected to high confining pressures are also important, given that these materials form part of the structure of the basal drains of these dams. The results of tests conducted on samples of porphyry copper tailings of the Andes Mountains of Chile and Perú, had been presented in several paper and thesis (Campaña (2011), Maureira & Verdugo (2012), Santos (2011), Solans (2010), among others) for low and high confining pressures up to 2,94 MPa.

5. Behavior of tailings sand dam

5.1 Failure in tailings sand dams in Chile

Tailings sand dams and hydraulic fill dams are both perceived to be relatively vulnerable structures that do not provide the same safety as conventional dams built for water impoundments or for power generation. This perception is related to the fact that the stability of sand dams depends on the geotechnical behaviour of hydraulically deposited sands subjected to a limited compacting effort, and therefore, supposedly susceptible to liquefaction. The regrettable history of tailings dam failures, several of them including fatalities and/or extensive contamination downstream from the dam, has prompted negative community perception. The description of some sand tailings dams failures in Chile has been mentioned by several authors (Troncoso (1993), Dobry (1967), Valenzuela (2015)). In all those failure cases in Chile the type of dam corresponds to no compacted upstream sand dams.

5.2 Success behavior in tailings sand dams

The date of 28th of March 1965, when the failure of El Cobre tailings dam occurred, became a milestone in the practice of design and construction of tailings dam in Chile. After 1965 no upstream tailings dams have been built in Chile, although a few older upstream tailings dams are still existent but not in operation and their gradual removal and in some cases, re-mining of the tailings is underway or next to. Table 2 presents a list of the main sand tailings dams that have been built after 1965. All of them use the downstream construction method except for El Torito dam that at a certain height changed from downstream to centreline construction method. None of these dams has suffer some significant damage during the relatively recent EQs of Valparaiso 1985 (Mw=8.0), Maule 2010 (Mw=8.8) and Illapel 2015 (Mw=8.4) although most of these dams are at a relatively short distance of the epicentres, as it is shown in Figure 3 for the case of the Illapel EQ of 2015. It is remarkable that all these sand dams correspond to a medium a large mining operation (>8 Kiloton per day) designed with the best practice available at the time.

Table 2: Main Sand Tailings dams built after 1965 (Valenzuela et al, 2020).

Name	Max height (§) (m)	Dam length (m)	Capacity (Mm3) (+)	Operation start	Type	Operation end
El Cobre 4	68	1,140	31	1969	DS	1992
Piuquenes	58	500	20.5	1970	DS	1980
Pérez C. 2	115-135	500	84	1978	DS	1992
Talabre	40	5,300	1451	1985 (*)	EF/DS	OP
El Chinche	110	470	14.5	1992	DS	1999
Las Tórtolas	150-170	1,700 (-)	690	1992	DS	OP
Torito	78	2,190 (+)	122	1992	DS/CL	OP
Quillayes	175-198	1,600 (+)	360	1999	DS	2008
Ovejería	58-120	3,600 (+)	235	1999	DS	OP
El Mauro	237	1,450 (+)	1088	2008	DS	OP

Note: The data shown are approximated, obtained from different sources. Some of the deposits have been expanded, not all them registered in this table. (-) Only main dam; (§) Approximate final height; (+) Approximately; (*) Deposition began in 1952, just in 1985 was necessary confinement walls. DS: Downstream sand dam; CL: Centerline sand Dam

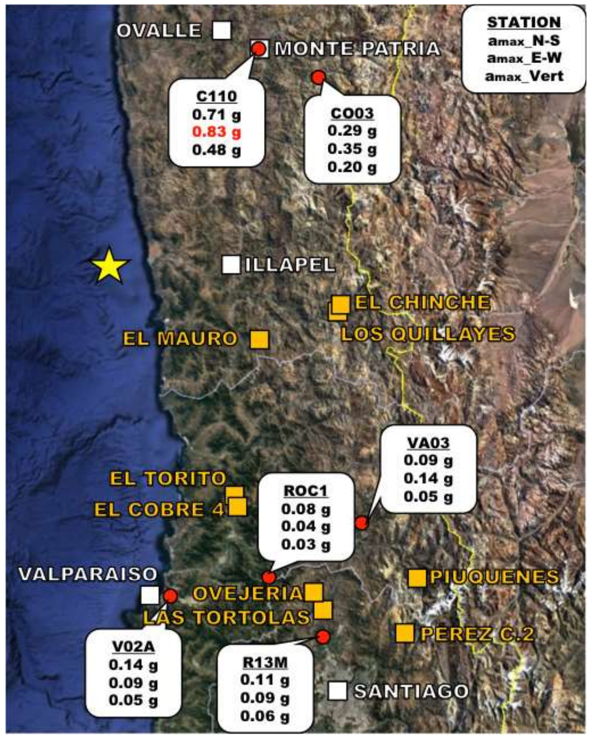


Figure 3: Tailings dams, close to epicentre Illapel EQ.

After the collapse of El Cobre dam in 1965, El Cobre N°4 dam (68 m high) was constructed in 1969 with the downstream method and using compacted sand obtained for the first time from tailings in a centralized cyclone station with strict control of fines content in the sand and hydraulic transport of the sand with positive displacement pumps. This design concept was later in 1978 applied at the Pérez Caldera N°2 tailings dam of 135 m high (*Valenzuela, 2015*) that was fully instrumented allowing to verify the high positive behaviour that this type of dam could represent. This concept was applied and improved in many details at Las Tórtolas dam, built in 1992 (170 m estimated maximum height) that has become internationally known as the representative example of what has been recognized as the Chilean sand tailings dam practice (*Valenzuela, 2015*) (*Morgenstern, 2018*). Other dams of this type are: El Chinche (110 m), Torito (78 m), Quillayes (198 m), Ovejería (120 m) and El Mauro (237 m). None of these dams that have followed the general concept applied at Las Tórtolas and use hydraulic fill of sands disposed directly on downstream growing slope have suffered any significant damage during EQs.

5.3 Las Tórtolas, Quillayes and Mauro sand dams

Las Tórtolas Tailings Storage Facility (TSF) is located at elevation 700 masl, 45 km north of Santiago, in Chile's central valley. In this dam, which cross section in shown in Figure 4, conservative design criteria included initially a double cyclone station to guarantee

10% maximum fines content (FC) in the sand. The design considered the implementation of a network of instruments, including piezometers and accelerometers. This is the first TSF that was subjected to a dynamic stability and deformational analysis using the finite differences method.

Satisfactory performance of this TSF, which began operating in 1992, made it possible to increase FC to 15% a few years later and to define a new maximum height of 170 m. The current height of this dam is near 110 m. Design of this deposit initially set a maximum capacity of 1,000 million tons of tailings, and recent estimates increased that capacity to 2,000 million tons. The deposit has two others smaller cyclone sand dams, all constructed using the downstream method. In the main dam, the starter dam consists of compacted earth 17 m high. Approximately 5 m of loose alluvial soil were excavated under the starter dam and under part of the sand dam, after which dynamic compaction was applied to the foundation. The dam is equipped with generous basal drains that were built in stages. The dam is constructed with cyclone sands compacted to 95% Proctor Standard. The sand was initially deposited forming a slope of 1:4 (V:H) to facilitate compaction with rollers. After a few years of operation, and after verification of very satisfactory dam performance confirmed by density controls and piezometric level records, the deposition slope was changed to 1:3.5 (V:H). A final slope of 1:3 (V:H) is considered for the closure stage (Valenzuela, 2015).

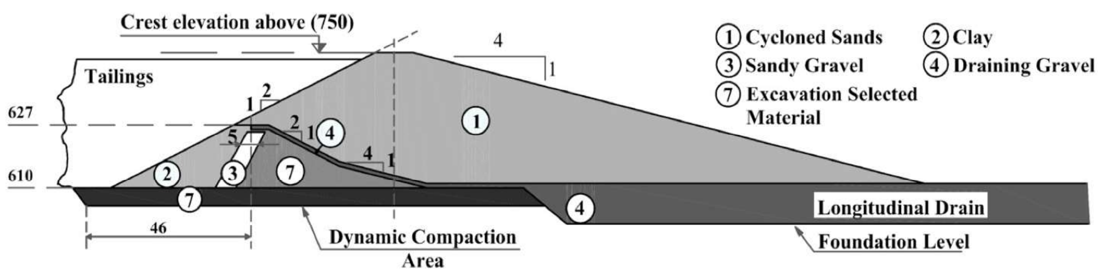


Figure 4: Cross section Las Tórtolas dam (Valenzuela, 2015).

Although this dam had not yet been built at the time of the Valparaíso EQ of 1985, there were already accelerometers installed in the rock at the dam site and the registers of this strong and relatively close EQ were considered later in the dynamic stability analysis of the dam. Two large EQs have been registered during the operation of the TSF: the February 27/2010, EQ Mw=8.8 and the September 16/2015 EQ Mw=8.4. In both seismic events, no-significant damage or deformation was observed. The instrument located in hard soil, associated with the main dam, recorded the data show in Table 3 (Campaña et al., 2015).

Table 3: Recordings of large EQs in Las Tórtolas Main Dam.

Date	M	Dist. (Km)	D (km)	Loc.	PGA (g)	PGA (g)	Vert. PGA (g)
March 5, 1985 (2)	Ms=7.8	~105	33	Basal soil Downstream	0,172 N64°E	0,144 N26°W	0,106
Feb 27, 2010	Mw=8.8	~420	30	Basal soil Downstream	0,18 N64°E	0,18 N26°W	0,129
Sept 16, 2015	Mw=8.4	~190	23	Basal soil Downstream	0,066 N64°E	0,064 N26°W	0,045

M= Magnitude according to U. de Chile
Dist.= Distance from epicentre to the dam
D= Depth of earthquake
Loc = Location site of the accelerograph
PGA= Peak Ground Acceleration (Horizontal)
Vert. PGA= Vert acceleration in g's

Note: (1) Baseline corrected (2) Epicentre data according to USGS. https://www.usgs.gov/

Another TSF of special interest is Quillayes at Los Pelambres mine, due to a series of conditions that represented complex design, construction, and operating restrictions. The mine is located 300 km north of Santiago with the Quillayes TSF located 6 km of the processing plant. The site is in the foothills of the Andes Mountains, at an average elevation of 1,400 masl, distant some 85 km from the Pacific Ocean. 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 (*Campaña et al., 2015*). The main dam is a tailings sand dam, constructed by hydraulic deposition of sands obtained from the cycloning of tailings, and it was 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. The dam foundation consists of fluvial deposits in the central area of the dam, colluvial deposits, and / or alluvial terraced deposits in the right abutment and intrusive rock (granodiorite type) in the left abutment.

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. Raising of the dam and tailings placement stopped at the end of 2008, when the new El Mauro TSF started to operate.

Static and pseudo-static stability analysis using limit equilibrium methods were performed. The deformations under seismic loads were estimated through different methods: The pseudo-dynamic analysis proposed by Makdisi and Seed (1978) and formal numerical analysis with FLAC2D and FLAC3D. Both numerical analysis (2D, 3D) did not show evidence of failure by shear resistance or excess of deformation that could affect the global stability. The design earthquake (Maximum Credible EQ) was of Mw=8.3, with epicentre 123 km from the dam an 23km of depth, with PGA of 0,37g (horizontal) and 0,25g (vertical) in hard soil. The September 16/2015 EQ of Mw=8.4 was at the same depth and remarkably close to the epicentre of the design earthquake. According to the post-EQ inspection by the Engineer of Record, non-significant deformations or instability was detected (Valenzuela, 2015).

The new Mauro TSF that replaced Quillayes TSF is locate 40 km approximately to the SE of Quillayes dam, 50 km to the Pacific Ocean and at an average elevation of 900 masl. This TSF was planned with maximum capacity of 1,700 million tons of dry tailings with 237 m of dam height. At the end of 2021 tailings filled near 44% of total volume authorized (*Consejo Minero, 2022*). The dam is raised following the downstream construction method, through continuous hydraulic deposition of tailings sands containing less than 19% fines (material passing ASTM 200 mesh), compacted to 95% Proctor Standard. The dam is equipped with generous basal drains that are built in stages. The inclined deposition surfaces are compacted by tandem bulldozers and smooth vibratory rollers, with 1:3 (V:H) downstream and 1:2 (V:H) upstream slopes (*Consejo Minero, 2022*). Static and pseudo-static stability analysis using limit equilibrium methods were performed. The deformations under seismic loads were estimated by formal numerical analysis with FLAC3D using geotechnical parameters defined according an extensive and complete test carried out under low and high pressures in samples with different fines content and densities. Numerical analysis did not show evidence of failure by shear resistance or excess of deformation that could affect the global stability. The September 16, 2015 EQ of Mw=8.4 was at the same depth and remarkably close to the epicentre of the design earthquake. Non-significant deformations or instability was reported.

6. Monitoring and Surveillance

Tailings dams are constructed over a period of several years along with the operation of the mine. It is common therefore for a tailings deposit, and consequently the construction and operation of the tailings dam, to take several years or decades. The long construction period inserted into an industrial operation presents opportunities and challenges for the optimal performance of these dams, not only from the geotechnical point of view and that of overall stability, but also for operational ease, safety, and cost.

The opportunities arise precisely from the long operation period, which, if adequately planned, permits application of the Observational Method (Peck, 1980), (*Morgenstern, 1996*). The Observational Method requires not only continuous supervision but also suitable instrumentation and control schemes for the periodic and sometimes continuous monitoring of the most important variables, such as static and dynamic piezometric levels, volumes of seepage flow, quality of water in drains, deformations in key points of the dam, and response of the dam to accelerations during earthquakes of some magnitude. In addition, the results obtained from instrumentation and from quality controls must be interpreted and analysed periodically by geotechnical specialists to introduce modifications that guarantee or even improve safety conditions of the tailings dam.

7. Design Criteria, Practice and Legislation

There were no specific requirements for tailings dams until the failure of El Cobre tailings dam in 1965. In 1970 a special decree N°86 (*Ministerio de Mineria, 1970*) was issued jointly by the Water Agency in Chile (DGA) and SERNAGEOMIN. This decree banned the construction of upstream tailings dam, being the first country banning a specific type of dam. The most recent legislation related to tailings dams in Chile is Decree N°248[1] (*Ministerio de Mineria, 2007*) that replaced Decree N°86 in 2007 and it establishes special conditions for sand tailings dams: the percentage of fines in the sand cannot be higher than 20% passing n° 200 mesh.

It should be emphasized that for “upstream tailings dam” it was designated the type of dam that was commonly built in Chilean mining before 1965, without compaction, poor or inexistent cycloning of tailings, steep downstream slopes and uncontrolled rate of dam raising. The Chilean legislation has not recognized other possible upstream construction procedures as it is the practice in other countries (*Williams, 2019*) (*McLeod, 2019*).

Centreline construction of tailings sand dams is certainly an acceptable construction method even in seismic environment if adequate design considerations are applied. The advantage is that this type of construction requires a smaller footprint area and volume of sands. But in many cases, this type of solution for high dams requires to maintain a much wider crest during construction and for closure. In centreline construction uncompacted, or poorly compacted sand has to be placed hydraulically over already deposited tailings and depending on the static and dynamic bearing capacity of these tailings or slimes it could be required to reinforce the tailings or slimes surface with geotextiles or rock dumping to avoid excessive sand sinking volume. This method presents potential difficulties when it is necessary to protect the sand body of the dam from contact with water in the case of floods or prolonged contact with free water. The placement of impervious membrane in centreline construction is much more difficult that in the case of downstream construction and sometimes an impervious core has been proposed instead. The selection of the construction type should be the result of a detailed comparison of benefits and operational difficulties. There is the example of Cerro Verde dam (*Obermeyer,2011*) in Perú of a very high centerline sand dam in a highly seismic area currently under operation with satisfactory performance. In that case the centreline method was considered the more adequate. The Chilean experience has favored the downstream construction.

[1] The Decree N°248 is under revision.

For all types of dams, except the banned upstream tailings dams, dam design and construction in Chile has considered the international best practices as they are developed, following recommendations of organizations like ICOLD, ICMM, CDA, MAC and others. The following are the characteristics that explain the adequate performance of sand tailings dams specially in such highly seismic country as it is Chile:

- Centralized cyclone station to guarantee quality of specified sand (fines content).
- Specification of maximum fines content between 15% to 20% to guarantee an ample contrast of permeability with that of the tailings or slimes deposited.
- Distribution of sand from the crest of the dam as it grows forming a gently downstream slope to facilitate sand compaction with bulldozers (typically between 3,5 to 4,0:1 (H:V).
- Sand compaction to a minimum of 95% Standard Proctor or equivalent to guarantee a dilatant behaviour of sand at least for a certain threshold of confining pressure.
- Generous drains, basal and lateral fingers, capable of instantaneously get rid of water during construction (operation) stage obtaining a low phreatic line at the level of drains. Once operation is finished the drains will have and extraordinary high capacity to guarantee adequate conditions at closure.
- Discharge of tailings and/or slimes over the upstream slope (typically 2H:1V). An impervious geomembrane is placed over the upstream slope to avoid the possibility of water to reach the sandy slope although in depth such membrane would be partially destroyed due to the drag downward forces produced by the consolidation of tailings, but at that moment the tailings and no the water will be in contact with the sand body of the dam.
- For tailing dams over 15m, is necessary to verify the physical stability using pseudo static method (FoS≥1.2) and dynamic analysis.
- Cohesion effect is not considered in dam design. This is a conservative design criterion. According to *Verdugo et al* (2017), unsaturated tailings sands with fines content less than 20% may have residual gravimetric water content around 11%, which reasonably may be associated with an apparent cohesion greater than 60 kPa. *Verdugo et al* (2017), points out that in the models of dynamic analysis, the resulting permanent displacements are negligible a when an apparent cohesion of 40 kPa is adopted, which is compatible with empirical observations in sand tailings dams after strong EQ.

8. Concluding Remarks

The Chilean experience can be considered as empirical evidence showing that tailings dams are safe structures if designed and constructed according to sound engineering concepts and following the recommendations of the best available practice. It is worth to note that Chilean dam engineering has developed during the last 40 to 50 years a considerable knowledge and experience specially with two types of dams that have performed quite successfully in the seismic conditions of the country: concrete face gravel fill dams founded on alluvial soils including a diaphragm wall for the case of for water reservoirs (Valenzuela et al, 2020) and downstream sand tailings dams that could reach heights over 200 m for the case of tailings deposits.

References

SERNAGEOMIN (2022), Servicio Nacional de Geología y Mineria. Datos públicos relaves en Chile. https://www.sernageomin.cl/datos-publicos-deposito-de-relaves/https://www.sernageomin.cl/datos-publicos-deposito-de-relaves/

Valenzuela, L. (2015). Tailings Dams and Hydraulic Fills. The 2015 Casagrande Lecture. 16th Panamerican Conference on Soil Mechanics and Geotechnical Engineering. Buenos Aires, Argentina. In Advances in Soil Mechanics and Geotechnical Engineering. Vol. 5: Geotechnical Synergy in Buenos Aires. Edited by A.O. Sfriso, D. Manzanal, and R.J. Rocca. Amsterdam, The Netherlands: IOS Press.

Valenzuela, L., Campaña, J. (2021). Seismic behavior of Chilean downstream sand tailings dams. Included in book "Tailings Management Handbook – A Life-Cycle approach". Edited by Kimberly Morrison. Society for Mining, Metallurgy & Exploration (SME). *www.smenet.org*

Lomnitz, C. (2004). Major earthquakes of Chile: a historical survey, 1535-1960. Seismological Research Letters, 75(3), 368-378.

Ruiz, S., & Madariaga, R. (2018). Historical and recent large megathrust earthquakes in Chile. Tectonophysics, 733, 37-56.

Madariaga, R. (1998). Sismicidad de Chile. Física de la Tierra, (10), 221. (In Spanish)

J. Campaña, (2011). Comportamiento de Arenas de Relave a Altas Presiones, MSc Thesis Universidad de Chile (in Spanish).

Maureira S. and Verdugo R. (2012): Cyclic response of tailings sands subjected to high pressure, Proceedings VII Chilean Geotechnical Conference. Concepcion. (In Spanish).

Santos, E., (2011): Comportamiento Monótono y Cíclico No-Drenado de Arenas de Relaves Integrales. Tesis Magister en Cs. de la Ing., mención Ing. Geotécnica, U. de Chile. (In Spanish).

Solans, D., (2010): Equipo Triaxial Monótono y Cíclico de Altas Presiones y su Aplicación en Arenas de Relaves. Tesis Magister en Cs. de la Ing., mención Ing. Geotécnica, U. de Chile. (In Spanish).

Troncoso, J.H (1993) The Seismic Failure of Barahona Tailings Dam, 3rd International Conference on Case Histories in Geotechnical Engineering, 1473-1479.

Dobry, R. and Alvarez, L., (1967). Seismic Failure of Chilean tailings Dams, Journal of the Soil Mechanics and Foundations Division, ASCE, SM6 (1967), 237-259.

Valenzuela, L., Verdugo, R., Campaña, J., Opazo, C.G., (2020). Safety Performance of Dams in Chile Highly Seismic Environment. Fourth International Dam World Conference, Lisboa-Portugal.

Morgenstern, N., (2018). Geotechnical risk, regulation, and public policy. The Sixth Victor de Mello Lecture. 9th Portuguese – Brazilian Geotechnical Congress, Salvador, Brazil.

Campaña, J., Bard E., Cano, C., Valenzuela, L., (2015). Registro Sísmico en Depósito de Relaves. IX Congreso Chileno de Geotecnia, Valdivia-Chile. (In Spanish)

Campaña, J., Valenzuela, L., Figueroa, A., & Alarcon, J. C. (2015). The Quillayes Sand Tailings Dam in Chile, Design and Operation. Tailings and Mine Waste, Vancouver.

Consejo Minero (2022). Plataforma Relaves Consejo Minero. *https://consejominero.cl/comunicaciones/plataforma-de-relaves/antofagasta-minerals-3/*

R. B. Peck, (1980). Where has all the judgement gone? The 5th Laurits Bjerrum Memorial Lecture, Canadian Geotechnical Journal, 17-4 (1980), 584-590.

N.R., Morgenstern (1996). Geotechnics and mine waste management. Proceedings, International Symposium on Seismic and Environmental Aspects of Dam Design: Earth, Concrete, and Tailings Dams. Santiago, Chile, Vol. 2, p. 5–26, Sociedad Chilena de Geotécnia.

Ministerio de Minería de Chile, DS Nº 86, Reglamento de Construcción y Operación de Tranques de Relaves, 1970, (in Spanish).

Ministerio de Minería de Chile, DS Nº 248, Reglamento para la Aprobación de Proyectos de Diseño, Construcción, Operación y Cierre de los Depósitos de Relaves, 2007, (in Spanish).

Williams, D. (2019). Challenges in tailings management. Global tailings workshop. University of Queensland, Brisbane.

McLeod, H.N. (2019). Challenges with upstream tailings dams. ICOLD – CIGB 2019 Symposium, Ottawa, Canada.

Verdugo, R., Peters, G., Valenzuela, L., Campaña, J., Bard, E., (2017). Evaluation of tailings dams subjected to large earthquakes. 19th International Conference on Soil Mechanics and Geotechnical Engineering. Seoul.

Obermeyer, J., Alexieva, T., (2011). Design, Construction and Operation of a Large Centerline Tailing Storage Facility with High Rate of Rise. Tailing & Mine Waste, Vancouver.

Evolution of Chilean Tailings Deposits and Dams before and after El Cobre Failure in 1965

Luis Valenzuela, Geotechnical Consultant, Chile

Jose Campaña, ARCADIS, Chile

Natalia Pizarro, ARCADIS, Chile

Abstract

Tailings system facilities (TSF) vary significantly along the Chilean territory depending on geography and climate conditions that impact in tailings transport systems, tailings deposits, tailings dams and water recovery schemes. The extremely high seismicity of the country affects especially at tailings dams. Most of tailings dams have been subjected in their lifetime to a major earthquake of magnitude larger than M ≥7.5 and at short distance from epicenter. Information regarding on how the different restrictions such as geography, climate, and seismicity has influenced the evolution of tailings dam design, including historical aspects related to Chilean engineering development are presented in the paper with several examples on different areas of the country. The evolution of Chilean TSF and tailings dam design and operation will be presented covering mainly from 1965 to the present time but some general references to the period before the failure of El Cobre tailings dam in 1965 are also included.

1. Introduction

The design, construction, and operation of tailings deposits in Chile represent an interesting case of how different solutions have been applied in various regions of the country, which are characterized by extremely different geographical, geomorphological, and climatic features although all of them subjected to very high seismic conditions. Some of the main different aspects and environment sceneries that influenced the solutions applied in different regions:

- The unique geographical characteristics of the country, a territory of about 4,000 km long (stretching between parallels 18°S and 56°S) but with an average width of about 200 km from the high Andes mountains (East) to the Pacific Ocean (West).
- A very large desertic region in the North of the country with average annual rain of less than 3 mm, a Central region with about 300 mm average rainfall and a relatively wet South region that ends at the Cabo de Hornos where the Pacific Ocean joins the Atlantic Ocean, with annual rainfall varying from 900 to 5,000 mm. Mining being concentrated in the North and Central regions.
- Most of the country is in the edge where the Nazca Plate subduct the South American Plate, what has made Chile be responsible for 40% of the energy liberated by EQs, mainly North of parallel 42°S.
- Chilean territory presents enormous mineral reserves, such is the case of copper with the biggest world reserves of this metal, but also important reserves in molybdenum, gold, and other metals as well as non-metallic deposit such as lithium and nitrates. These ore reserves are in general at North of parallel 35°S (metallic) and at North of parallel 25°S (non-metallic). There are some coals and poli metallic deposits in the South region but of less economic importance.

The Chilean relief is made up of the Andes mountains, the Coastal mountains, the intermediate depression, and the coastal plains. The intermediate depression crosses longitudinally all the country, flanked by the two mountain systems, and it extends heterogeneously from the extreme North of Chile to the South, with a constant decrease in altitude as latitude increases. In general terms, the topographical features, the geological conditions, and climatic differences throughout Chile, lead to define different geographic zones in the Chilean territory where most of the Tailings Storage Facilities (TSFs) have been developed. In the paper an arbitrary geographical zoning will be used when commenting the different tailings dams in the country. These zones have been defined as:

a) **North zone**, covering the political regions (provinces) of Tarapacá and Antofagasta.

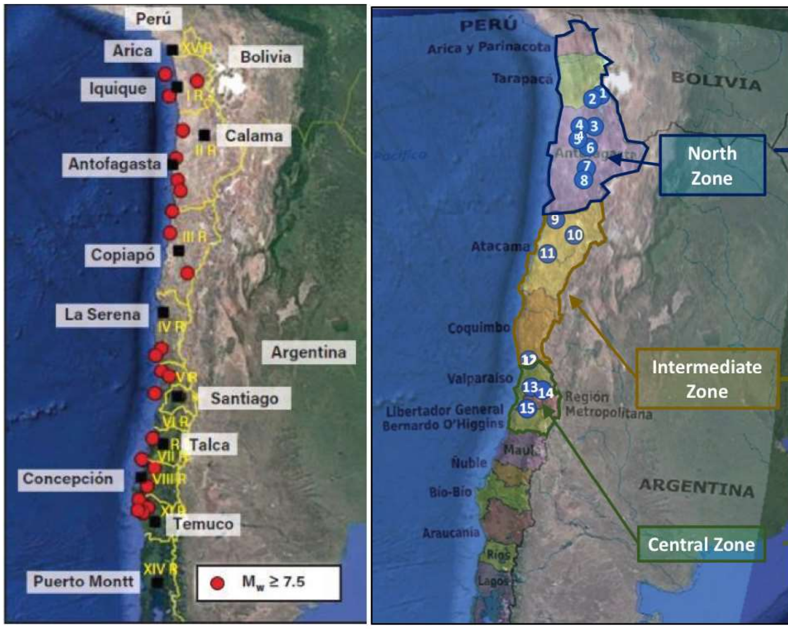
b) **Intermediate zone**, covering the political regions of Atacama and Coquimbo.

c) **Central zone**, covering the political regions of Valparaiso, Metropolitan and O'Higgins as well.

It should be noted that this somehow arbitrary division is only an approximate zoning, and some deposit examples could eventually not fit exactly in one of these zones.

2. Tectonic and seismic background

Chile is one of the most seismic countries in the world. The Valdivia earthquake (EQ) of 1960 with a moment magnitude (Mw) = 9.5 is the greatest EQ ever regis¬tered. In February 2010, the Maule EQ (Mw = 8.8) occurred, which is the world's six larger EQ. In September 2015, the Illapel EQ (Mw = 8.4) occurred located about 300 km North of Santiago (Campaña et al. 2022). Since 1906, about 23 EQs with Mw ≥7.5 have occurred In Chile. It is estimated that a large earthquake of Mw≥ 8.0 occur every 10 to 20 years while giant mega earthquakes of Mw≥ 8.5 occur at the average rate of two per century (*Ruiz and Madariaga, 2018*). Figure 1 shows, the three regional zones that have been defined for the purpose of discussing TSF evolution, together with some of the registered strong EQs with Mw ≥ 7.5. Most TSF and tailings dams have been subjected by, at least, 2 to 3 EQs of high magnitude.



ID	TSF Name
1	Quebrada Blanca
2	Pampa Pabellón
3	Talabre
4	Spence
5	Sierra Gorda
6	Esperanza
7	Zaldivar
8	Laguna Seca
9	Pampa Austral
10	La Coipa
11	Candelaria
12	El Mauro
13	Ovejería
14	Las Tórtolas
15	Carén

Figure 1: Identification of some strong EQs with Mw ≥ 7.5 and examples of TSF's located in the three regional zones that have been defined.

3. Historical background before 1965

Starting of relatively organized mining activities dates to middle of XVI century, when Spaniards conquered what today is Chile, focused mainly on the gold exploitation at a larger scale than previous Inca´s exploitation, but declining in XVII century when the richest ore deposits got exhausted. There was a significant revival of mining in the XVIII century focussed on gold and silver and high-grade oxidized copper minerals, all exported to Spain. The first part of XIX century saw a silver rush and early coal mining.

In the last part of XIX century mining activity grew significantly with what has been defined as the saltpetre (potassium nitrate) era, approximately between 1870 – 1930. But also, the copper exploitation grew with mining activities done by relatively small mines but also with new international investments in copper exploration and mining. Up to today small and medium size mining coexists with some of the world larger mining companies.

The modern froth flotation process was invented only on the 1900s in Australia, so the production of tailings of flotation process as it is known today did not exist and most of the mining was focussed on processing oxidized copper ore or even hand – picked extraction of very high-grade ore. With the development of flotation tailings deposits started, and in a bigger scale during the first quarter of the XX century.

The Chuquicamata copper mine in the North zone (the largest copper mine at certain point), started its production about 1880 (same place that has been mined since the Inca´s time). It became a modern mining operation about 1910 with an investment of the Guggenheims Brothers and based on leaching processes. It was sold to Anaconda Copper in 1923. By 1951 the oxidized reserves were primarily exhausted, then a mill, flotation plant and smelter were built to treat supergene copper sulphides. The tailings were deposited in natural depressions without dams. Talabre TSF and dams were initially built around 1980.

The second big copper mine is El Teniente, in the Central zone. It was exploited at a low production level since 1819 and about 1903 the mine was sold to Barton Sewell, later Braden Copper Company, starting the operation with a concentration plant of 3 ktpd in 1908. In 1916, the 95% of the stocks were sold to Kennecot Corporation. When the production increased, a relatively big TSF named Barahona 1 was built in 1917 near the flotation plant with a sand tailings dam using upstream construction. This dam failed in 1928 during the Talca EQ of M =7.7 causing 54 fatalities. The dam was replaced by Barahona 2, also an upstream sand dam that became inactive in 1936.

The fact that the 2 major big mining companies of the country at that time, operated by international groups, were not able to apply adequate tailings dams design and construction during their first 50 or more years of operation, explains the low standard and poor performance of many of the numerous tailings deposits and dams built and operated the country in the 3 zones already mentioned.

According to *Sernageomin, 2022* (data updated to 2020), in Chile there are 757 tailings deposits, and only 112 deposits significative size are active. The status of the other deposits is defined as “in construction” (5), “inactive” (467) and many of them mainly in the North Region are considered “abandoned” (173). Figure 2 shows the distribution of the TSF’s.

The catastrophic failure of El Cobre dam in 1965 because of La Ligua EQ (Mw=7.4) that provoked more than 200 casualties (*Valenzuela & Campaña, 2021*, *Campaña et al. 2022*), constitutes a turning point in the development of tailings dams in Chile. Before 1965 most of the tailings dams were built using the upstream method of construction, with limited tailings segregation, sometimes using small cyclones operating from the dam crest and generally relatively steep downstream slopes. Many of those dams required a high rate of rising without allowing time for drying and desiccation. As a result of El Cobre failure, the upstream method of construction was banned in Chile in 1970 through Decree 86 issued by the Ministry of Mining. Besides, the new regulation required to determine of "dangerous distance" to nearest population, becoming a first approach to Dam Break Analysis (*Valenzuela, 2021*).

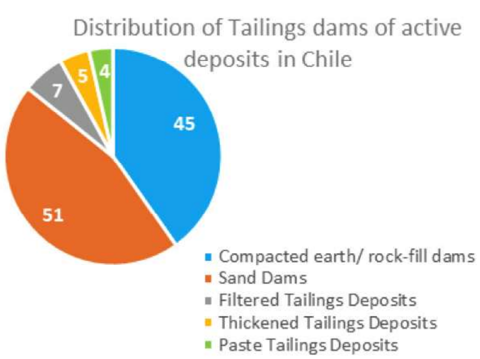
There are still some failures of small dams, most of them upstream type or poorly constructed inactive dams that had occurred in the last major earthquakes of 1985 (Mw=8.0) and 2010 (Mw=8.8) with only Las Palmas dam failure, with 4 fatalities (Valenzuela et al, 2020).

It is worth noting that the concept of liquefaction was established formally only in 1935 by Prof. Casagrande and its final formulation confirmed in 1969 by the Chilean engineer Gonzalo Castro (Casagrande, 1975).

Since 1970 the Chilean mining industry and dam engineering adapted the design and construction of tailings dams to modern concepts accepting the ban of upstream construction and focusing on projects of tailings dams with downstream construction methods considering compacted sand dams as well as conventional embankment dams with borrow materials and waste rock fill. The centerline construction method in Chile is not forbidden, but it has not been widely implemented.

4. Type of tailings dams most used in Chile

The 112 deposits classified as active (*Sernageomin, 2022*) are mainly made up of sand dams and embankment dams constructed with borrowed and/or waste rock materials. Figure 2 shows the distribution of each type of dam and the geographical distribution along Chilean territory. Figure 2 also indicates the existence of 16 active deposits of no conventional tailings conformed by filtered (7), thickened (5) and paste (4) tailings deposits. There are also 4 active deposits located in the southern regions of Chile.



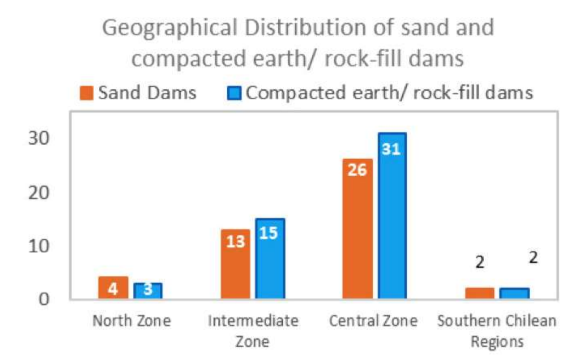


Figure 2: Distribution of tailings dams types of active deposits in Chile.

Tailings sand dams has been the most used type of dam in the mining industry, as in many cases it is markedly cheaper than other alternatives, such as compacted earth or rock-fill dams, although in some cases the use of waste rock represents also a relatively economic solution if it was available at a short transport distance. The sand dams are built with the coarse portion of the tailings (sand obtained at cyclone´s-underflow), separated by centrifugal mechanical cyclone while the fine portion is deposited into the pond (slime- overflow).

Compacted earth and waste/rock fill dams are the second most used type of dam in the mining industry in Chile and if only current active deposits are considered, the amount of this type of dams is practically equivalent to downstream sand dams. In most cases compacted rock fill dams have a low permeability core with an impermeable layer on the upstream face of the dam to prevent excessive seepage.

Since 1960 the copper production had a great evolution, increasing the rate of waste generation. This fact combined with the need of reducing the environmental impacts and the scarcity of suitable available land, has resulted in a direct impact on the overall size and magnitude of tailings dams. Figure 2 shows the development of the accumulated volume of large tailings deposits according to the register of the Chilean government mining institution (Sernageomin). It should be noted the first important increase in mining activity around 1950 and then in 1980 a sharp increase in deposited tailings that continues up to nowadays. In the same Figure 2 is shown the register of the main individual authorized tailings deposit.

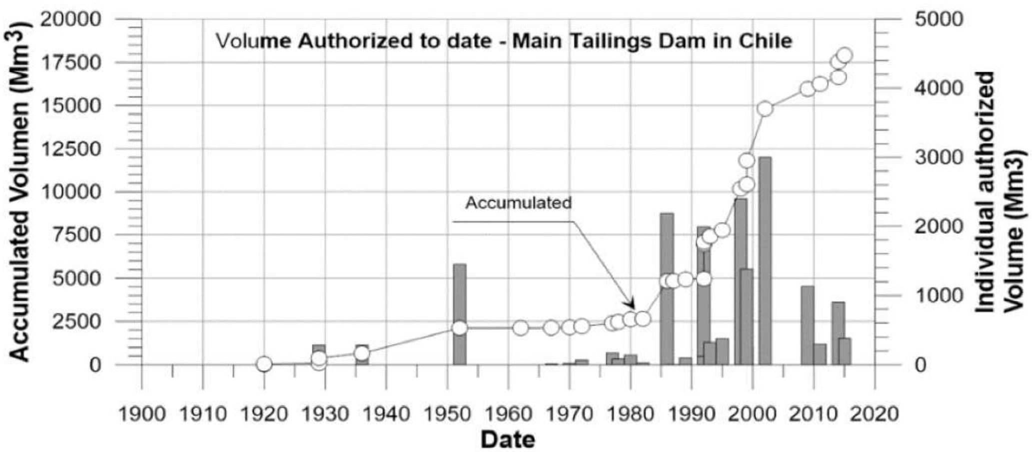


Figure 2: Accumulated volume and authorized deposits (Valenzuela et al., 2020).

5. Examples of Chilean Tailings Deposits and Dams Design

The features of the TSFs and tailings dams developed in Chile depend largely on the geographical location because of the specific topographical and climate conditions already commented. Besides, some relevant aspects that have influenced the selection and design of TSF are tailings production rate and volume, seismicity, rainfall level and flood occurrence, water availability for tailings transport systems, proximity to communities and the fulfilment of local regulations and the application of international guidelines and industry best practices. The definition of the North, Intermediate and Central Zones shown in Figure 1 have been used to help in the understanding of the impact of local conditions in the selection of dam's characteristics. Except for Talabre, Candelaria, La Coipa, El Mauro, Tórtolas and Carén, the deposits presented below are located relatively far from the communities.

5.1 North Zone tailings dams' examples

In general, in the North Zone there are only few TSFs constructed in valleys with very steep sides, and most of TSFs are developed in flat floored areas, relatively near of the mines. Examples of these are Quebrada Blanca 2, Pampa Pabellón, Talabre, Laguna Seca and Centinela. Figure 3 shows the location and the typical cross section of these TSFs.

Quebrada Blanca 2 (Teck) is a conventional deposit (no thickening), currently in construction, 7 km south the Concentrator plant of QB2 with a total capacity of 1,250 million tons (Mts). The starter dam is a waste rock compacted dam of 120 m height. The design considers a centerline sand dam of 310 m height above the starter dam with a HDPE geomembrane in the upstream slope. The expected discharge is about 140 ktpd and a basal drainage system will be extended as the foot of the dam growths downstream.

Pampa Pabellón (Collahuasi) is a conventional deposit 3 km from the concentrator of Rosario Mine. The operation started in 1998 and the system includes 3 dams with maximum heights of 39, 44 and 127 m. Currently just the main dam (127 m) is in construction with compacted waste rock and downstream method. The current tailings discharge is 210 ktpd and the authorized capacity of the TSF is 1,040 million tons (Mts).

Talabre (Codelco) is also a conventional deposit of 60 km2 composed by 3 main dams with maximum heights of 38, 36 and 51 m and with lengths of 3, 11 and 4 km. The current discharge is about 220 ktpd coming from Ministro Hales and Chuquicamata mines. It is programmed to change disposal system to thickened tailings with a discharge rate of about 400 ktpd. The first 6th stages of the main dams were downstream construction and mechanical sand placement. From the 7th stage centerline construction with waste rock will be used. The TSF is located approximately 15 km East of both mines and the current authorized capacity is 2,059 Mts.

Laguna Seca (Minera Escondida) is a conventional deposit which operation started on 2002. The dam is downstream construction with compacted sandy borrow material of 107 m maximum height (52 m current height). It is located approximately 4 km from Laguna Seca concentrator plant, the authorized capacity is 4,500 Mts. Current disposal rate is about 450 ktpd. The estimated final area of the TSF is about 62 km^2, with a perimeter of 37 km.

Centinela (Antofagasta Minerals) is the first thickened tailings storage facility (TTSF) implemented in Chile and currently the biggest thickened tailings facility in the world (318 ktpd programmed). The operation started in 2011 and the approved capacity is 750 Mts. The original design considered 65% of solid contents (sc) and a tailings beach slope of 4,5%, but the initial results of the operations have resulted in 2%.

The original design had to be adapted and currently the tailings disposal and the thickener systems incorporate new tailings rheological information and lessons learned from the operation. The current TTSF is named Esperanza and the project incorporates the construction of a new TTSF identified as Centinela that considers the construction of a confining embankment of 163 m height and 11 km length with rockfill and waste rock material. The authorized tailings discharge is 138 ktpd for stage 1 and 318 ktpd for stage 2.

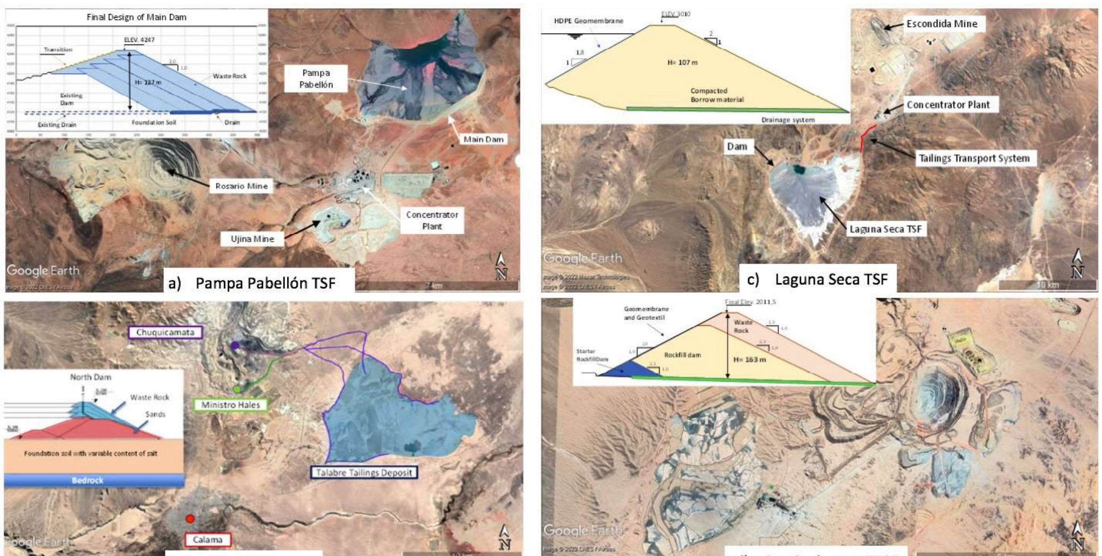


Figure 3: Location and typical cross section of TSFs examples from North Zone - Generated from SEA, 2022 data.

5.2 Intermediate Zone tailings dams' examples

In the Intermediate Zone the valleys are narrower than in Norte Grande and the availability of extensive flat areas decreases. The lack of space and the proximity to communities downstream of the deposit are predominant factors to selection of TSF type definitions. Some of the main TSFs that operate in this area are Pampa Austral, Candelaria, La Coipa and Mauro. Figure 4 shows the location and the typical cross section of these TSFs.

Pampa Austral (Codelco) is a TSF with conventional deposition in Atacama Region which operations started in 1990. The design considered a main dam with 36 m height with compacted borrowed material and downstream construction and a geomembrane on the upstream slope. The authorized capacity is 354 Mts. The TSF is located 60 km from El Salvador town. The nearest community is Diego de Almagro, about 15 km from the TSF.

Candelaria (Minera Candelaria) is a conventional deposit. The operation started in 1994 and concluded in 2019 with 541 Mts deposited. The design considered 3 waste rock dams with downstream construction with maximum heights of 180, 43 and 50 m. The South dam was waterproofed with HDPE liner while the other dams used the tailings themselves. This TSF is currently used as an emergency deposit as Los Diques is the new TSF. Candelaria is in the upper part of a ravine, with the dam been practically buttressed by the waste rock dump placed immediately downstream of the dam and close to the open pit (*Barrera et. al, 2022*).

La Coipa (Mantos de Oro) This gold mine has built one of the biggest filtered tailings deposits of the world. The tailings generated, with a Cp of near 80% in weight are transported by conveyor belts to the main TSF Rahco (100 Mts of tailings deposited). The tailings have been deposited by radial arm stacking conveyor in lifts approximately 1,0 m thick. The maximum height is 200 m (current height is 150 m), the total surface area of the deposit is 0,3 km^2 and the authorized capacity is 147 Mts. There is also an emergency deposit Rakito (with 21 Mts deposited and 20 m height), occasionally utilized. The distance between the TSF and the concentrator plant is less than 3 km.

El Mauro (Los Pelambres Mine) is a conventional TSF located in Coquimbo Region. The operations started in 2009 and the authorized capacity is 1,700 Mts. The design considers a cyclone sand dam with downstream construction. A geomembrane is placed over the upstream slope. The current height is about 172 m while the expected maximum height is 237 m. Before El Mauro, Los Pelambres mine used to discharge the tailings at Los Quillayes deposit, also a downstream sand dam located nearer the concentrator plant. Los Quillayes operated until 2008 reaching 198 m height. Mauro TSF is 60 km from the concentrator plant.

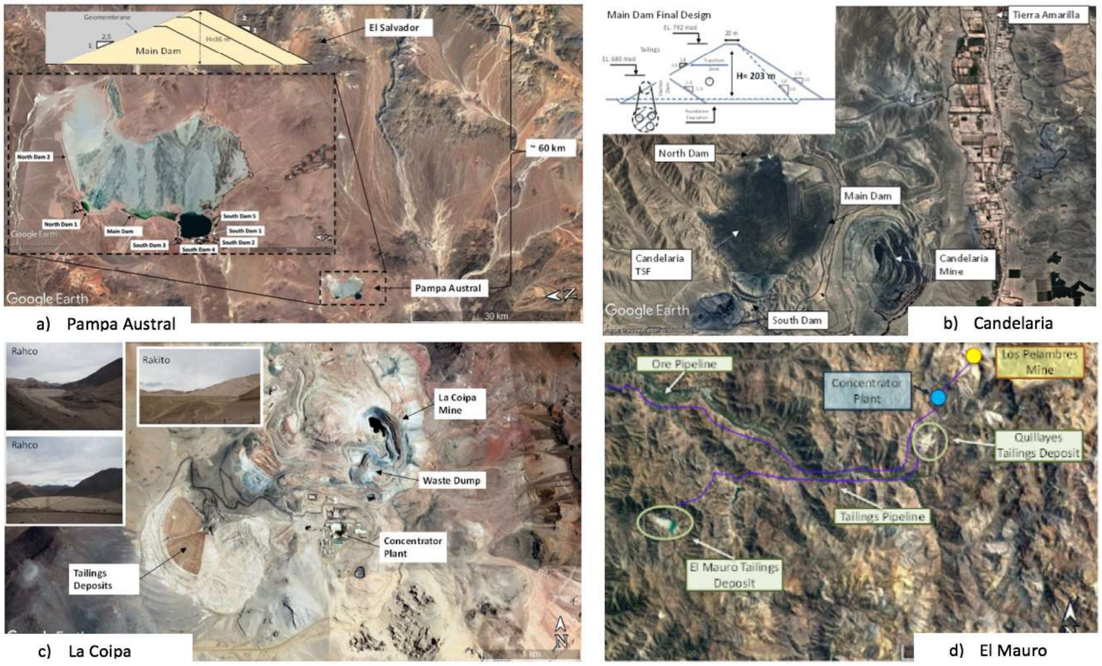


Figure 4: Location and typical cross section of TSFs examples from Intermediate Zone. Generated from SEA, 2022 data.

5.3 Central Zone tailings dam's examples

In Central Zone the relatively abrupt topography in the mine areas with more limited capacity to deposit tailings with reasonable dam heights has generated the need for new disposal areas, resulting in TSFs quite distant the concentrator plants, requiring tailings transport systems of great lengths. Some examples are Las Tórtolas, Carén and Ovejería deposits. Originally these operations deposited their tailings in deposits at higher elevations, nearer the concentrator plants. Increasing productions required new and larger capacity TSFs. Figure 5 shows the location and the typical cross section of two of these TSFs.

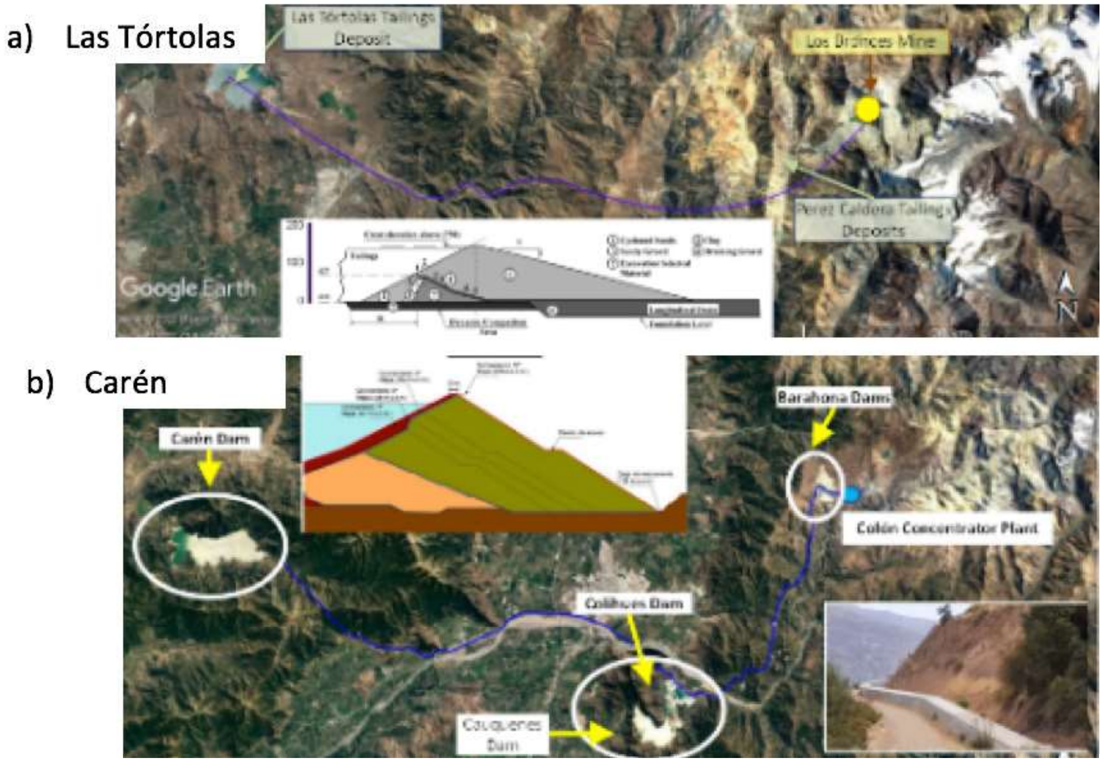


Figure 5: Location and typical cross section of TSFs examples from Central Zone.

Las Tórtolas (Anglo American Sur S.A.) is a conventional TSF of Los Bronces mine located about 3,000 m.a.s.l. The operation of this deposit started on 1992. The design incorporates 3 downstream sand dams with expected heights of 183, 183 and 90 m with an impervious geomembrane in their upstream slopes. The authorized capacity is 1,900 Mts and the current tailings production is about 143 ktpd. The crushed ore slurry is transported to concentrator plant, located near of the TSF, through a 56 km pipeline with 2,500 m of topographic unevenness. Until 1992, the old operations up in the Andes used to discharge the tailings in 2 downstream sand dams Perez Caldera N°1 (66% currently removed) & N°2 (9% currently removed). Total removal of older tailings to Las Tórtolas, is depending on water availability in the region.

Carén (Codelco) is a conventional deposit that receive the tailings from El Teniente mine since 1986. The tailings are conveyed from concentrator at elevation 2,300 m.a.s.l in a concrete flume 86 km long. Before Carén, since 1917 to 1936, the tailings from El Teniente were deposited in Barahona 1 and 2 TSFs formed by upstream sand dams located near Colón concentrator. Between 1936 and 1986 El Teniente utilized Colihues and Cauquenes TSFs, located about 30 km downstream Barahona. Currently the old tailings deposited in Cauquenes are being reprocessed by Minera Valle Central (MVC) and the residual tailings are discharged in the concrete flume to Caren. The annual average tailings flow conducted by the system is 175 ktpd, which includes the reprocessed tailings of Cauquenes TSF.

Carén TSF considers the downstream construction of two compacted embankment dams with borrowed material. The projected final height of main dam is 136 m, while the auxiliar dam maximum height is about 46 m. The current design contemplates a geomembrane in the upstream dam slopes. The authorized capacity of Carén deposit is 3,330 Mts.

6. Conclusions

The failure of dams could occur due to various causes, such as undetected weak foundation soils, static and seismic liquefaction, large deformations under strong EQs, unsuitable construction materials and other causes. In the case of water reservoir dams their design generally considers all the possible causes when selecting their location, favoring sites where these possible failure causes are minimum or can be mitigated with a proper design.

In the case of tailings dams it is not always feasible to solve restrictions that are own characteristics of the mining operation, such as: location of the mine; location of concentrator; relative distances between mine, concentrator, and available sites with enough storage capacity; distance from potential deposit sites to downstream communities; changing and increasing production levels; construction period of many years or decades; and site adequate conditions for closure of the deposit.

This complex challenge can be confronted with appropriate holistic designs considering the geography, the seismic and tectonic environment, climate, hydrological and geological conditions, and nearby communities when selecting a site and a type of deposit and tailings dam. The proximity to communities needs to be included and evaluated at the initial stages of the project, since tailings facilities can have major impacts on communities through the construction and operation stages as well as at closure.

It should be noticed that upstream dam construction implemented in Chile before Decree 86 did not used to consider enough time for tailings desiccation, consolidation and subsequently a degree of compaction, for improving the tailings bearing capacity. Nowadays there are some successful examples of this type of construction and operation implemented in other countries with gentle downstream slopes, good water management, appropriate rate of rise of tailings and some compaction effort.

The paper has presented examples on how the geography, climate and production level has influenced not only the site selection but also the type of tailings dam. With time other requirements will appear for instance from new climate data, new demands of communities in terms of physical stability but also chemical stability, new technologies, new pressures to diminish water consumption and other requirements that will make necessary to reinforce, modify or improve the physical characteristics of these deposits as well as its performance.

References

A. Casagrande, Liquefaction and Cyclic Deformation of Sands – A Critical Review, *V Panamerican Conference on Soil Mechanics and Foundation Engineering*, (1975), 81-133.

Barrera, S., Riveros, C., Soto, V., Recabarren, C. (2022). Candelaria TSF – a holistic approach. Copper 2022.

Campaña, J., Verdugo, R., Valenzuela, L. (2022). Seismic Performance of Chilean Tailings Sand Dams. Copper 2022.

Ruiz, S., & Madariaga, R. (2018). Historical and recent large megathrust earthquakes in Chile. Tectonophysics, 733, 37-56.

SERNAGEOMIN (2022), Servicio Nacional de Geología y Minería. Datos públicos relaves en Chile – Catastro de Depósitos de Relaves en Chile (Actualización 10-08-2020). https://www.sernageomin.cl/datos-publicos-deposito-de-relaves

Valenzuela, L., Campaña, J. (2021). Seismic behavior of Chilean downstream sand tailings dams. Included in book "Tailings Management Handbook – A Life-Cycle approach". SME.

Valenzuela, L., Verdugo, R., Campaña, J., Opazo, C.G., (2020). Safety Performance of Dams in Chile Highly Seismic Environment. Fourth International Dam World Conference, Lisboa-Portugal.

Valenzuela, L. (2015). "Tailings Dams and Hydraulic fills". Casagrande Lecture, XI Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Buenos Aires, Argentina.

SEA – Servicio de Evaluación Ambiental. Datos Públicos de Estudios y Declaraciones de Impacto Ambiental de los depósitos de relaves de Chile. Consultado con fecha 12.04.2022. https://www.sea.gob.cl/