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Seismic performance of tailings sand dams in Chile

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Abstract

An extremely high and frequent seismic activity coincides in Chile with the existence of numerous tailings dams associated to the copper industry. In the country there is a history of tailings dam failures since the early XX century and up to today. Nevertheless since the decade of 1960 there have been a growing number of new large tailings dams that have had a very good performance even when subjected to very strong earthquakes. The paper summarizes the instructive history of failures as well as of successes of the newly designed tailings dams and particularly of the sand tailings dams. Different aspects of the main new sand tailings dams such as the design criteria, tailings sand characteristics under high confining stresses are discussed. These aspects are complemented with information on major earthquakes occurred in Chile in the last years, especially of El Maule Earthquake of Magnitude 8.8 of February 27, 2010 and the location of main tailings dams in the zones impacted by this earthquake. Finally, discussions are included with regard general seismic performance of tailings sand dams, seismic deformations, and seismic instrumentation including dams in operation and dams already inactive.

Keywords: Tailings dams, Seismic behavior, Sand dams, Tailings sands, Dynamic properties of sands.

1. Introduction

Chile is probably the most seismically active country in the world, contributing with a high percentage of the total seismic energy released worldwide. In the last 60 years several earthquakes with magnitude greater than 8.0 had occurred in their territory with the Valdivia EQ in 1960 (M_w = 9.5) and Maule EQ in 2010 (M_w=8.8) among them. On the other hand Chile is well known as the world largest copper producer, being responsible for the production of about 2.5 millions of tons of copper tailings each day. These tailings have to be deposited in "reservoirs" formed by one or more dams that are raised as the deposits grow. The most common, efficient and economic type of dams used in these deposits are those built using the sandy portion of the tailings as the main construction material, although under specific site conditions conventional earth dams and waste rock fill dams have been constructed. Depending on how the dams grow, these tailings dams could be classify as upstream, downstream or centerline dams as shown in Fig. 1.

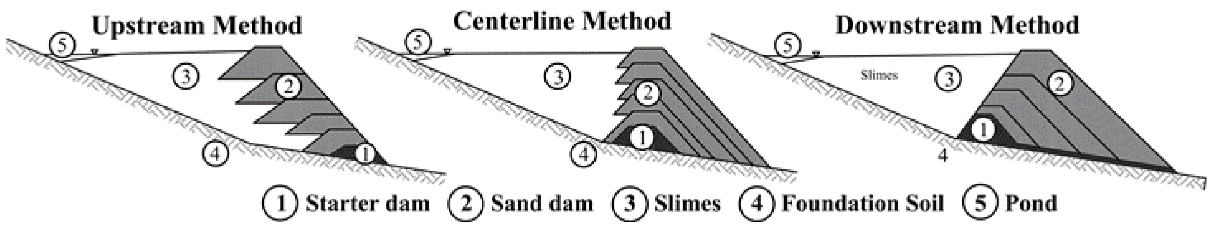


Fig. 1 – Type of tailings dam depending on the growth method.

The experience in high seismic regions indicates that tailings dams are sensitive to earthquakes; in fact several seismic failures have been reported. However, most of these seismic failures have been described in tailings dams constructed under upstream method. Properly designed tailings dams constructed by the downstream and center-line methods have had in general a very satisfactory performance under seismic conditions. In the case of Chile, where the seismicity is very high and the mining industry is very active, several hundred tailings dams are distributed in the territory, and a non-neglected number of tailings dams mainly constructed by the upstream method have experienced failure due to earthquakes.

2. General worldwide performance of tailings dams

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. Fig. 2 shows statistics of failure[1] of conventional dams and tailings dams reported between 1800 and 2000, according to ICOLD [1] [2].

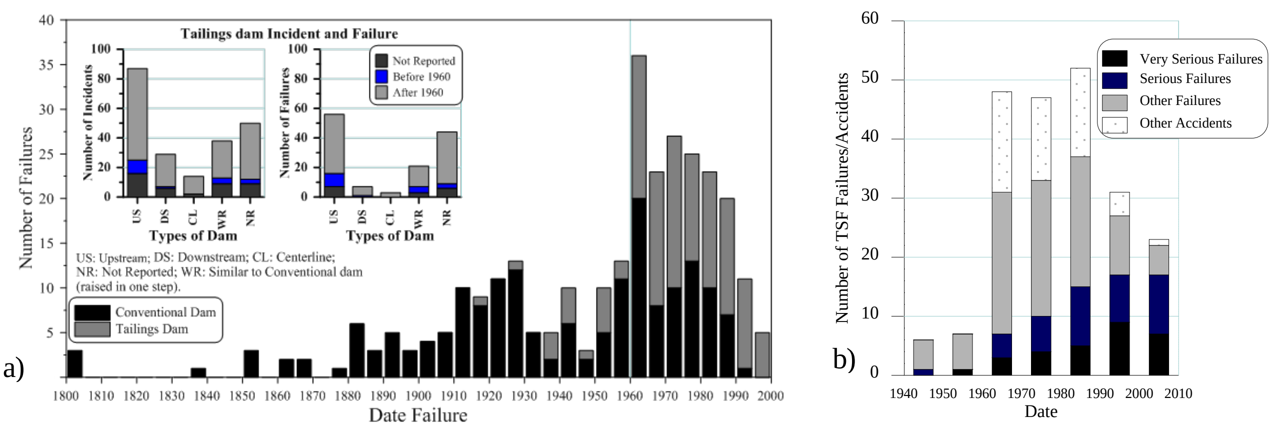


Fig. 2 – (a) Statistics on dam failures according to ICOLD [1] [2]. (b) Increasing severity of TSF Failures Globally[2] [3].

[1] Incidents include three categories, according to USCOLD [4] : failures, accidents, and groundwater. Failure is defined as breach of an embankment leading to release of impounded tailings; accident is defined as physical damage to the embankment that does not result in release of impounded tailings; groundwater is defined as the failure of an engineered design feature to control groundwater contamination in the manner intended.

[2] Serious failures is defined as a release of greater than 100,000 m^3 of tailings and/or loss of life. Very Serious failures is defined as a release of at least 1 Mm^3 of tailings, and/or a release that travelled 20 km or more, and/or multiple deaths (generally ≥ 20).

Figure 2 shows that, during the period between 1800 and 2000, the recorded number of tailings dam failures represents 40% of the total number of failures. However, this percentage increased considerably between 1960 and 2000, reaching 70%. This increase occurred in the period when the mining industry, especially metal mining, experienced a major production increase.

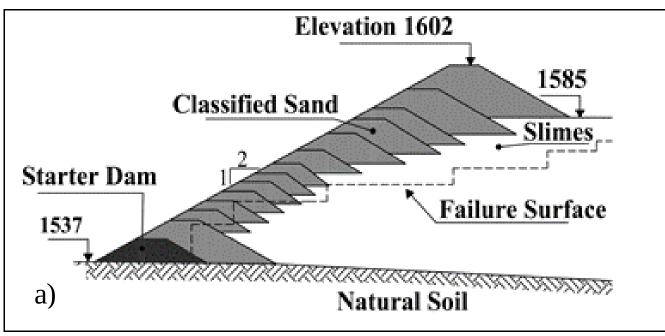
Published statistics have shown that tailings dams constructed using the upstream method have frequently suffered some type of incident, as shown in Fig. 2. Historically, upstream dams have been the most common and numerous tailings dams, as they are more economical in both investment and operating cost. In relative terms upstream dams continue to fail most often, especially in highly seismic countries such as Chile and Japan.

As will be shown below, the Chilean experience constructing downstream tailings dams is significantly favorable, with no seismic failure reported even after very large earthquakes.

3. History of tailings dam failures in Chile

In Table 1 are listed the main reported failures of tailings dams in Chile [5][6][7][8][10][11][12] most of which corresponds to upstream sand tailings dams that failed as a consequence of a major earthquake. Among those failures the most important ones are the failures of Barahona dam and El Cobre dam.

The Barahona N° 1 tailings dam, that failed during December 1, 1928 earthquake, is located in the Andes mountain range at an elevation of 1,650 masl at El Teniente mine, 80 km south-east of the city of Santiago in the central zone of Chile. The failure has been described by Agüero [5], Troncoso et al [6] and Troncoso [7] and it occurred as a consequence of a magnitude Mw = 8.3 event, with its epicenter at 180 km from the dam. The dam was 65 m high, and it had been growing upstream, during 8 years, with tailings sand dikes partially founded on fine tailings slimes, and a resulting downstream slope of 2H:1V. As the earthquake hit the dam, with probably more than 30 cycles of strong accelerations, the recently deposited slimes underwent liquefaction, upper dikes close to the left abutment settled, transverse cracks opened, slimes flowed and eroded downstream, progressing until the dam collapsed along a 200 wide breach, and some 2.7 million cubic meters of tailings were released. The liquefied tailings descended through the course of Barahona Creek, entered Coya and Cachapoal Rivers, mixed with the natural waters, flowed first over steep gradients and flooded lower areas located as far as 30 km downstream. The energy of the flow destroyed first a local private railroad of the mine, station and bridges and, most unfortunately, a camp site located 12 km downstream at the riverside, causing the death of 54 people. In this dam, as in other similar ones, low undrained resistance of slimes contributed to the failure. Fig. 3a shows a cross-section of the dam before and after the failure, according to Troncoso et al [6]. The new dam Barahona 2 was designed to grow as a downstream sand dam, which behaves satisfactory during the M_w=7.8 earthquake of March 3 1985 [6] as well as in February 27 2010 (M_w=8.8) and September 16 2015 (Mw= 8.4) earthquakes.



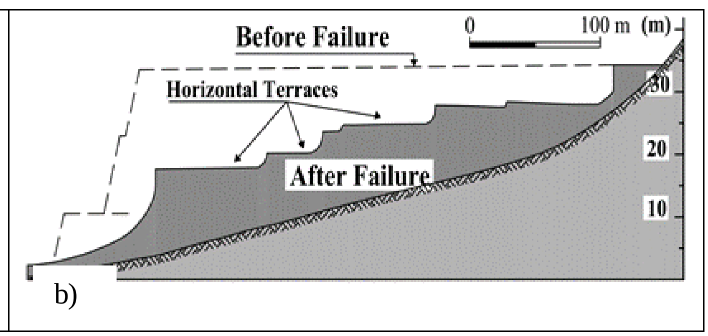


Fig. 3 – (a) Cross-section of the Barahona N°. 1 dam, showing the failure mechanism [6], (b) El Cobre Old dam profile before and after the failure [8].

The failure of El Cobre Old and New Tailings Dams is also well known for its disastrous consequences: more than 200 people dead, and widespread contamination of an agricultural valley. The failure occurred during the March 28, 1965 Mw = 7.4 earthquake in central Chile, the epicenter of which was only 40 km away from the dam. The details have been described by Dobry and Alvarez [9]. The El Cobre New Dam was an upstream dam, and its failure was due to liquefaction of sands and tailings flows (Figure 3b). Flow failure caused erosion and also flow failure of the Old Dam which was located closely downstream. Further upstream of these two upstream dams there was another dam (El Cobre 3) that did not fail which was at one time modified to operate briefly in a combination of downstream / centerline growth.

During the 1965 earthquake there were some eight other tailings dams, mostly from small mines, which also failed. The failure of El Cobre dams, plus the history of Barahona 1 and other smaller dams, caused the Government of Chile to issue the first code of Design and Operation of Tailings Dams in 1970 (DL 86). This Code stated that tailings dams had to be built by downstream or centerline methods, discouraging upstream method of growth.

Another instructive case is the failure of Cerro Negro Nº4 tailings dam in March 3, 1985 (Mw=7.8) earthquake, as described by Castro and Troncoso [13]. This deposit was in operation, actually as a centerline dam, at the time of the earthquake and failed by liquefaction of the slimes, subsequent large displacements of dike at the crest, breaching, erosion and flow failure. Shear strength data obtained two year after the failure, close to upstream slope, disclosed profiles of standard penetration resistance (SPT) and residual undrained strength (Su) which revealed existence of transition wedges underlain by softer slimes in a narrow zone between the pond and the sand dam. The flow failure of Cerro Negro Nº4 was also instructive for analyses of prediction of endangered areas downstream a dam. The evidences left after the failure in the form of 3 to 4 m high mounds of solid tailings soils in the closer 2 km and destruction of road embankments and fences in 5 km, plus witnessed times of arrival of the flow at different distances, allowed Troncoso and Lobos [14] to verify the capability of a dam break model to estimate the heights of wave and velocity of flow for the topographic conditions of the site.

As indicated in Table 1, some six tailings dams were affected by the 2010 Maule earthquake in Chileon February 27, 2010, Mw=8.8 . This earthquake was the sixth largest earthquake recorded worldwide, and involved a nearly 500 km-long rupture N-S zone between the Nazca and South American plates, approximately between the cities of Concepcion and San Antonio.

Table 1 – List of main failures of tailings sand dams in Chile

Dam name	**Year**	**Fatalities**	**Height (m)**	**EQ Magnitude**
Barahona	1928	54	65	Ms = 8.3
El Cobre Old dam	1965	> 200	35	Ms = 7.4
El Cobre New dam	1965		19	Ms = 7.4
Veta del Agua N° 2	1981	-	30	Ms = 6.5
Cerro Negro	1985		50	Ms = 7.8
Veta del Agua N° 1	1985		24	Ms = 7.8
Planta Chacón	2010		-	Mw = 8.8
Planta Bellavista N° 1	2010		14	Mw = 8.8
Veta del Agua N° 5	2010		17	Mw = 8.8
Las Palmas	2010	4	15	Mw = 8.8

The Chilean experience indicates that even in earthquakes of great magnitude, all failures have occurred mainly in upstream dams. An extensive list of tailings dams failures in Chile has been presented by Villavicencio et al [12]. Every one of the dams that failed was relatively minor in terms of height and impounded volume, had been either improperly closed without maintenance, or were operative but with low technical requirements and poor quality control.

Figure 4 includes the graph prepared by Conlin [15] and complemented by Lo et al [16] and Verdugo [17], showing several of the upstream dams that have failed, according to the magnitude of the earthquake and the distance from the epicenter in the case of each dam, indicating a possible boundary between the two types of behavior.

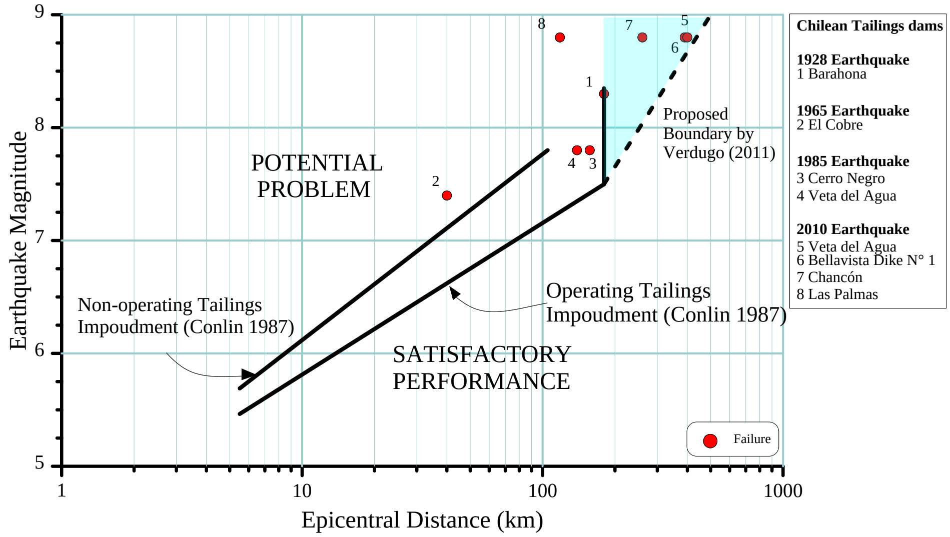


Fig. 4 – Susceptibility of upstream tailings dams to suffer damage due to earthquakes (Conlin [15]; extended by Lo et al [16] and by Verdugo [17]).

4. Seismic performance of tailing sand dams built after 1965

After 1965 and mainly after 1970 all tailings dams have been built following the new regulation i.e. considering downstream growth or center line. These tailings dams have been constructed with compacted borrow soil, waste rock fill or tailings sand. The large tailings sand dams built after 1965 are shown in Table 2.

Table 2 – List of large Chilean tailings sand dams post-1965.

Name	Max. Height (m)	Max Height ICOLD (m)	Dam Length (m)	Capacity (Mm3)(+)	Initiation of Operation	Type	End of Operation
El Cobre 4*	68	70	1140	31	1969	DS	1992
Pérez C. 2*	115-135 (§)	175	500	84	1978	DS	1992
El Chinche	100	144	470	14.5	1992	DS	1999
Las Tórtolas*	150-170	197	1700 (-)	1000	1992	DS	OP
Torito*	78	80	2190	130	1992	DS/CL	OP
Quillayes	175-198	240	1600 (+)	253	1999	DS	2009
Ovejería*	130	137	5000 (+)	1380	1999	DS	OP
El Mauro	237	265	1450	1088	2009	DS	OP
Piuquenes*	58	60	500	20.5	1970	DS	1980

Note: The figures shown in Table 2 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; (*) Dams located in Chile's central zone; DS: Downstream Sand Dam; CL: Centerline Sand Dam;

All the important tailings dams constructed after 1965 for the medium-scale and large-scale mining industry (sectors that have adequate organizational structures to handle tailings deposits and especially to construct and operate their dams), included those listed in Table 2, have performed satisfactorily, including many that were subjected to relatively close major seismic events (M>7.0). Only the Piuquenes dam (around 1970) and the Pérez Caldera N°2 dam (1978) have suffered some accidents not related to seismic events, though with no serious consequences.

None of the new dams, from which the main sand dams are included in the above list, have suffered damage of some significance even in the stronger earthquakes. Some of these dams have attained important heights, such as the Quillayes dam, which recently ended operation after reaching a height of 198 m (240 m according ICOLD height definition). Later in the paper a more detailed discussion is dedicated to Quillayes dam.

Recently, two large seismic events have hit the Central part of Chile: the 2010 Maule Earthquake of Magnitude 8.8 and the 2015 Illapel Earthquake of Magnitude 8.3. The peak accelerations recorded during these earthquakes are presented in

Fig. 5. It can be seen that the maximum local recorded horizontal accelerations were 0.93g and 0.83g, for the Maule and Illapel earthquakes, respectively.

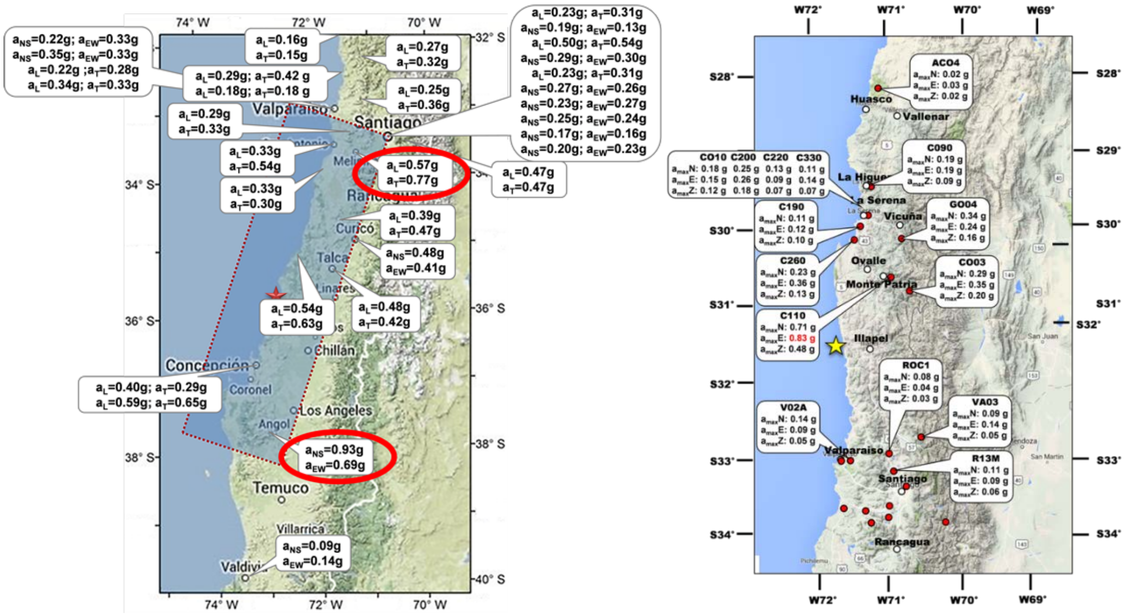


Fig. 5 – PGA recorded during the Maule – 2010 and Illapel – 2015 Earthquakes

The particular locations of large tailings dams placed in the epicentral area of these earthquakes are presented in Fig. 6. Additionally, tailings dams that underwent seismic damages during the Maule earthquake are also shown by yellow dots. The rupture zones involved in the generation of these mega earthquakes are sketched in Fig. 6. As can be observed, large subductive earthquakes present a rupture zone with an extension of hundreds of kilometers, making somehow diffuse the concepts of epicenter and epicentral distance.

The important empirical evidence provided by these two recent large earthquakes is associated with the good seismic behavior of all the large tailings dams that were subjected to the significant inertial forces induced by the shaking. Therefore, it is possible to conclude that well designed and carefully operated tailings dams are seismically stable.

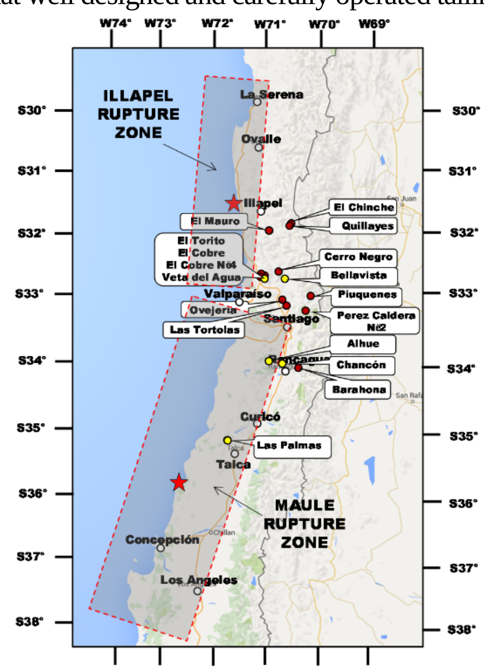


Fig. 6 –. Tailings dams and rupture zones of Maule and Illapel earthquakes

5. Examples of Chilean sand tailings dams

In the section, we describe and discuss two Chilean downstream tailings sand dams that are representative of the Chilean practice**.**

Las Tórtolas main dam. The Las Tórtolas tailings deposit is located at an elevation of 700 masl, 45 km north of Santiago, in Chile's central valley [10]. Studies of this dam, initiated in 1984, analyzed in detail the experience gained up to that date in El Cobre N°4 and Perez Caldera N°2. The adopted design included a maximum final height of 150 m, some 30 m higher than Pérez Caldera N°2. In this dam, shown in cross section in Fig. 7, conservative design criteria included 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.

Satisfactory performance of this dam, which began operating in 1992, made it possible to increase FC to 15% a few years later and to define a new final height of 170 m. The current height of this dam is 90 m. 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 rest of the foundation consists of denser gravelly sands. The downstream slope of the starter dam was constructed with a very shallow gradient in order to facilitate initial deposition of sands. The dam is equipped with generous basal drains that were built in stages. The dam is being constructed with cycloned sands and compacted to 95% Proctor Standard. The sand was initially deposited forming a slope of 1:4 (V: H). 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.

Recently, the dam was subjected to the 2010 Maule earthquake, magnitude Mw=8.8 and its aftershocks. The distance from the epicenter was 360 km, and 107 km from the rupture plate zone. No significant damage or deformation was observed. During that seismic event, only an increase of the piezometric level was registered. This was measured in three piezometers located in the starter dam, showing an increase in piezometric level corresponding to 3% to 5% of the thickness of tailings above the starter dam, levels which recovered within a short time [10].

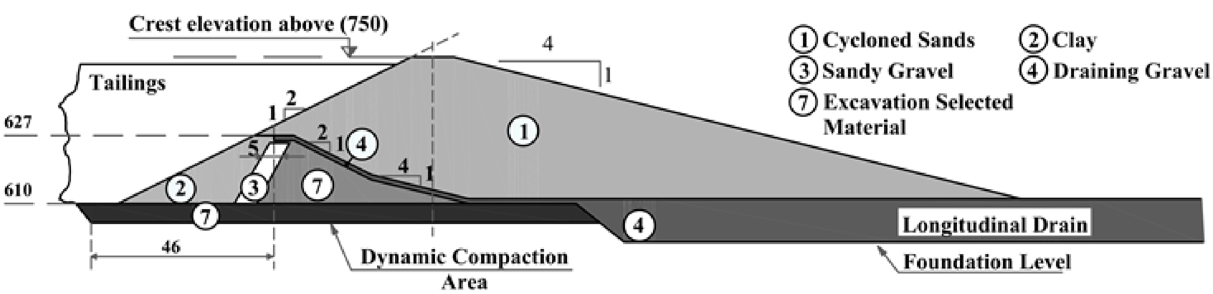
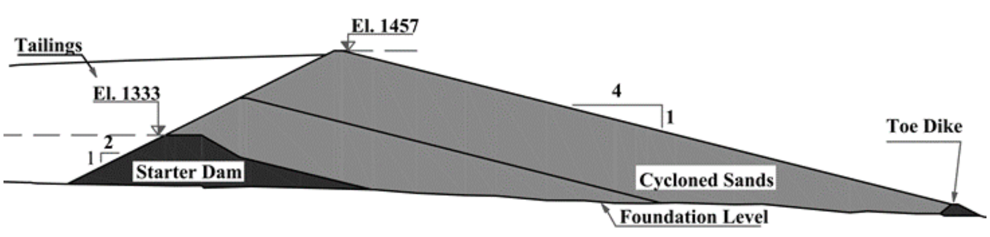


Fig. 7 – Cross-section of the main dam of the Las Tórtolas tailings deposit [10].

Quillayes tailings sand dam. The Quillayes tailings sand dam is of special interest, due to a series of conditions that translated into major design, construction, and operating requirements. The low impoundment/dam ratio and the high daily production of tailings to be deposited, some 100,000 TMPD, determined the need for a 70 m-high starter dam constructed of compacted clayish sandy gravel. It was necessary to cyclone 100% of the tailings to produce enough sand for the dam to grow at the rapid rate required during the early years, reaching a record 37 m above the starter dam crest during the first year. The cross-section of the dam is shown in Fig. 8.



Parameter	Original Design	Revision
Relative Density (%)	59	60
Friction Angle (º)	35-35.7	35
CRR	0.21	0.24
FC (% below#200)	15%	16%
Permeability (cm/s)	$10^{-3} – 10^{-4}$	$10^{-3} – 10^{-4}$
Phreatic level (m)	10	< 10

Fig. 8 – Cross-Section of the Quillayes Dam [10]. Comparison of geotechnical design and construction parameters [18].

Construction of this downstream tailings sand dam was begun in November 1998 and completed in July 2008, after deposition of close to 78 million m3 of sand to the dam's maximum height of 198 m. Up to one million m3 of sand were deposited and compacted per month while the deposit was in operation. The tailings produced in the concentrate plant consisted of a sandy slime with 80% in weight of soil with a size of approximately 212 microns and 50% fines under 200 mesh. Sands were specified to contain a maximum of 18% fines, and up to a maximum of 20% of samples were accepted with a content of maximum 20% fines. Sands were obtained from a fixed automated cyclone station installed at a convenient height on the right abutment of the dam, consisting of two sets or clusters of 20 cyclones each.

In 2002, the mining company commissioned a technical audit of the dam construction that included SPT and SCPT drillings, seismic refraction profiles, and test pits to determine density, permeability, and resistance of the dam sands [18]. Geotechnical characteristics of the deposited sands and of the pertinent design criteria are shown in Fig. 8.

Since the year 2008, the deposit has no longer received tailings and has acted as an emergency impoundment between the concentrate plant and the new El Mauro tailings deposit.

In September 16, 2015 a 8.4 (Mw) earthquake occurred with epicenter 71.864°W y 31.553°S, that is about 120 km from the Quillayes dam. Depth of earthquake was estimated in 11 km and ground accelerations in the region were of the order of 0.3 g, although there is one register of 0.83 g due to special soil conditions. Duration of strong motion was of the order of 50 s in agreement with a fracture of 100 km.

The design of the dam in 2000 included the verification of the seismic response of the dam for a similar earthquake: the Illapel earthquake of 1943 a 8.3 (Mw) estimated at a depth of 23 km and epicenter in the same zone that the 2015 earthquake. A peak ground horizontal acceleration of 0.37 g was considered in the analysis and a vertical acceleration of 0.25 g. A FLAC 3D seismic analysis showed the following deformations: horizontal (toe) < 1 m; horizontal (top) < 1 m; vertical (crest) < 0.5 m. Maximum crest acceleration 0.6 g. Unfortunately, no accelerations records are available of the 2015 real event at the site, however the seismic performance of the dam was very satisfactory with observed deformations limited to a couple of less than one centimeter wide longitudinal tension cracks close to the upstream border of the crest.

6. Design earthquakes in the design of Chilean sand tailings dams

In the case of Chile, under a subductive seismic environment, different seismic sources that are possible have to be included in the seismic stability analysis. This implies three potential seismic sources; interplate (thrust), intraplate (intermediate depth in-slab earthquakes caused by down-dip tension in the subducting plate) and cortical (shallow crustal earthquake). Seismologists have also identified the occurrence of outer rise (beyond the trench) earthquakes, however, from engineering point of view they are irrelevant, so they are generally neglected.

Because the seismic stability has to be guaranteed for the abandon dam condition, the design earthquake is related to long term seismic activity, involving large return periods. Accordingly, the three following seismic scenarios are recommended to be considered: Operational Basis Earthquake (OBE), Maximum Design Earthquake (MDE), and Maximum Credible Earthquake (MCE).

It is important to mention that the construction stage of any tailing dams is rather long, which provide the unique possibility for retrofitting, and therefore, the normal occurrence of small and medium earthquakes permit, to some extent, the verification and eventual correction of the numerical seismic analysis based on the measured seismic response of the tailings disposal. The MCE, associated with the post-closure condition of the tailings disposal, represents the ultimate possible seismic loading under which the tailings facility has to remain in place without collapsing. For the stability analysis of the post-closure condition, it is strongly recommended to include the effect of aging on the cyclic strength of the tailings, which is explained below.

7. Liquefaction Resistance of tailings sands

7.1. Influence of fines content on the liquefaction resistance

There are sufficient experimental evidences showing that the mechanical properties of silty sands are largely controlled by the amount of fines and by the plasticity of these fines [19] [20] [21] [22]. Cyclic triaxial tests performed at a confining pressure of 2 kg/cm^2 (196.1 kPa), on specimens of tailings sand with different low plastic fines content and compacted at the same initial void ratio, showed a clear degradation of the cyclic strength as the content of low plastic tailings fines increases (Troncoso y Verdugo, [19]). This effect is shown in Fig. 9 in terms of cyclic stress ratio and the number of cycles required for developing 100% of pore water pressure build-up.

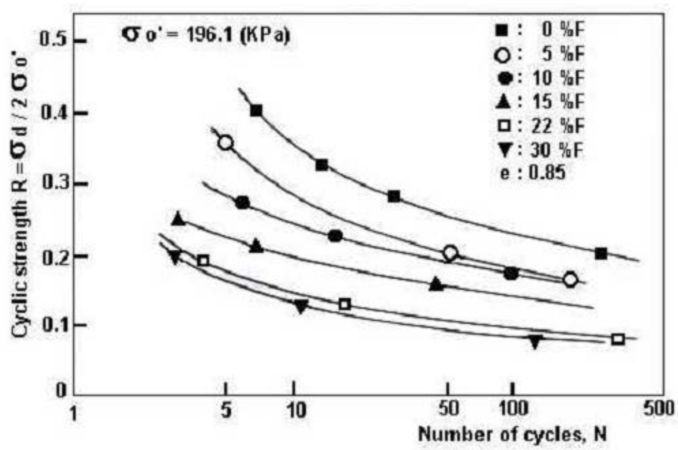


Fig. 9 – Effect of low-plastic fines on the cyclic strength of tailings sandy soils

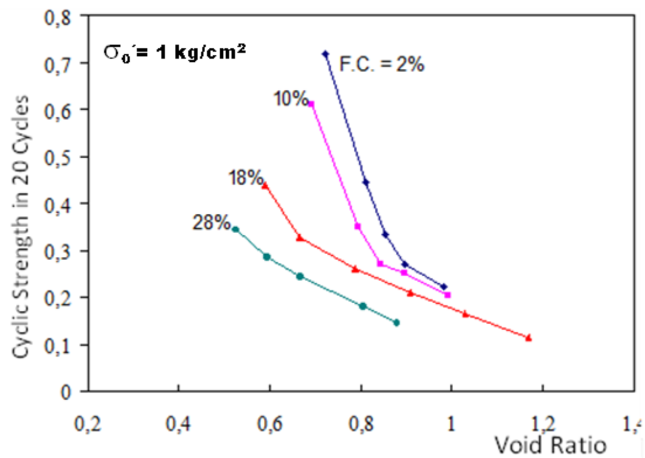


Fig. 10 – Cyclic strength in 20 cycles as function of void ratio for different fines contents

The results of a comprehensive study about the effect of low plastic fines on the cyclic strength of tailings sand are shown in Fig. 10. These are the results of cyclic triaxial tests on reconstituted samples with different fines content and densities (Verdugo and Viertel, [21]). For the range of fines content between 2 and 28%, the cyclic strength (defined for 20 cycles to reach 100% of pore water pressure build-up) consistently decreases as the fines content increases, regardless the void ratio of the samples.

For the range of fines content tested, the permeability is not likely to change in a drastic way; therefore, a big change in the seepage throughout the dam would not be possible. Hence, the saturated zone would not vary too much. In this scenario, it is possible to find the optimal combination of fines content and degree of compaction that minimized the cost, maintaining the required cyclic strength.

On the other hand, Campaña [23] has shown that at high confining pressure the effect of fines on the cyclic strength tends to disappear. Typical experimental results are shown in Fig. 11 for a tailings sand with 15 and 21% of fines, tested under a confining pressure of 15 kg/cm2 (1.5 MPa).

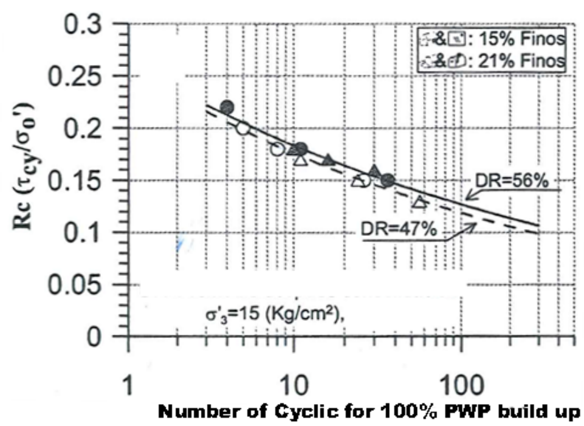


Fig. 11 – Cyclic strength at high confining pressure [23]

7.2. Effect of aging on the cyclic strength

The geological age of a sandy soil deposit has been recognized as one important factor that contributes to increase the cyclic strength, which can be attributed to the development of some degree of cementation or welding in the contacts between grains.

Experimental results regarding the effect of aging have been reported by Troncoso et al [24], which are shown in Fig. 12. Cyclic triaxial tests were carried out on "undisturbed" samples retrieved from different depth of an old tailings dam. Different depths actually mean different age of the samples. For comparison, tests on fresh reconstituted samples of the same tailings sand in the laboratory were also performed.

From the reported data it can be concluded that the cyclic stress ratio required to produce a state of softening in a 5% double amplitude strain, tends to increase by a factor of 3.5, 2.4 and 2,0 for samples of 30, 5 and 1 years of sustained deposition, respectively.

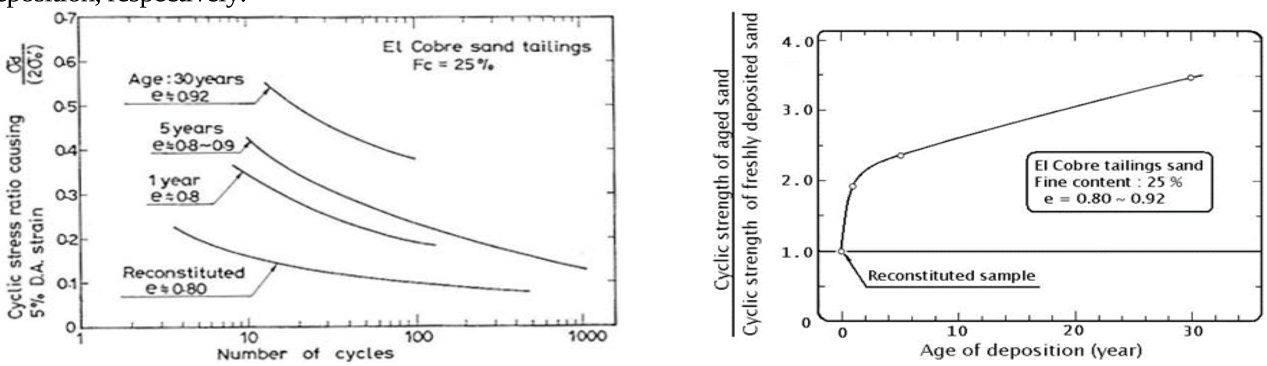


Fig. 12 – Aging effect on the cyclic strength of tailing sand

Hence, for the stability analysis of the abandon condition, it is strongly recommended to include the effect of aging. This type of study can be done when the tailings dam has been in operation for several years, and retrieving samples at different depths is absolutely possible. From test results, the variation of the cyclic strength with the age of deposition can be evaluated, allowing an estimation of the improvement of the cyclic resistance in time.

7.3. Effect of level of confining pressure on the cyclic strength of tailings sands

The effect of the confining pressure on the cyclic strength has been taken into account through the correction factor, Kσ (Seed [25]). This factor has been experimentally evaluated for different tailings sands, which results are presented in Fig. 13. It is observed that Kσ decreases sharply up to a confining pressure of the order of 5 to 10 kg/cm2 and thereafter it remains basically constant up to the confining pressure of 50 kg/cm2 applied in the tests.

For natural sands the effect of confining pressure on the cyclic resistance is significant, with values of Kσ as low as 0.4 at pressure of 8 kg/cm2 [27]. Accordingly, the experimental results on tailings sands indicate that the effect of confining pressure on the cyclic resistance is less important in tailings sands than in natural sands. This is an important conclusion that should support testing programs at high confining pressure according to the level of stresses existing in the dams. This result would allow avoidance of over design caused by an excessive reduction of the liquefaction resistance in large dams.

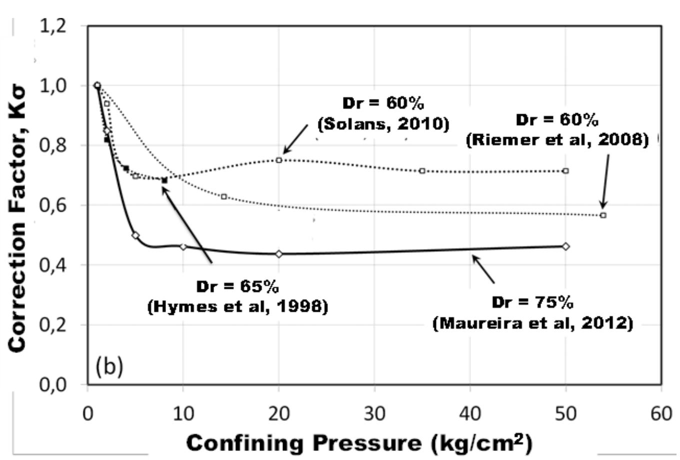


Fig. 13 – Correction factor Kσ for different tailings sands

8. Seismic Instrumentation and Monitoring.

Seismic instrumentation is a very useful tool to monitor the behavior and the evolution of tailings dams. Accelerograph stations are fundamental sensors to record responses of the dam and foundations to earthquake loadings. Chilean present practice considers at least 3 stations for each dam: one in rock outcrop, to represent characteristics of incoming waves at the site; one on free field close to the foot of the dam, to represent base input, and one at the crest. This basic array allows to analyze time histories of motions at the site: peak rock and ground accelerations, frequencies, spectra and duration, and amplification effects of the dam.

Accelerometers provide information about the evolution of dynamic characteristics of the dam as the geotechnical structure grows, consolidates and ages, allowing feedback of changes in stiffness and natural period of vibration as different earthquakes hit during the life of the dam and leading to more realistic predictions for future performances. However, to obtain full benefits from the instrumentation system it is most important to have dedicated expert care for maintenance, information retrieval and analyses of records under supervision of specialized earthquake geotechnical engineer to avoid troubles or to loose records, as unfortunately have occurred, when reliable and fast responses are most needed.

Most important variables for seismic behavior are the dynamic pore water pressures which under shear stresses may decrease inside dilative sands but increase inside compressive sands, eventually liquefy and lead to flow failures, as indeed has occurred in cases mentioned in previous sections. Therefore, seismic instrumentation is highly improved by interconnection of accelerographs with dynamic piezometers, because time histories of pore water pressures build-up are recorded together with accelerations in real time [26]. Such in-situ records of dynamic pore pressures are most necessary to evaluate and to predict seismic pore pressure increments under actual states of stress, in undisturbed fabrics and with complex drainage boundaries, given the difficulties to replicate these conditions and to generate realistic data in the laboratory.

Seismic instrumentation and monitoring are useful tools to prevent occurrence of failures of tailings dams because these dams grow rather slowly while they remain exposed to earthquakes over years of operation. Dangerous tendencies in performances may be detected and quantified in earlier stages of life and reinforcements may be timely implemented.

9. Final Remarks

Seismic performances of sand tailings dams in Chile have been analized for dams built during one century, before and after the 1965 catastrophic failure of El Cobre dam. Many older facilities were only operated, according with the experience of some mining personnel and without much involvement for engineering design or supervision. Upstream method of growth was conveniently used to form deposits of low cost and located as close as possible to mining plants. Unfortunately the lessons of the earlier failure of Barahona dam had not been sufficiently disseminated to change general practice toward safer designs. Afterwards, studies of both seismic failures plus investigation of soil dynamic and liquefaction effects caused by strong earthquakes, which occurred between 1960 and 1965, greatly improved the state of knowledge and practice. As a consequence dynamic design methods were implemented and upstream mode of growth was officially banned. Satisfactory performances of modern tailings dams, as shown in this paper, illustrate the benefits of such improved methods of design and expert monitoring of operation of tailings dams.

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