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ARTICLE

Failures of sand tailings dams in a highly seismic country

Gabriel Villavicencio, Raúl Espinace, Juan Palma, Andy Fourie, and Pamela Valenzuela

Abstract: Chile is one of the main copper producers in the world. It is located in a geographical area where mega-earthquakes occur and this fact, together with the development of larger and higher sand tailings dams (with some facilities currently under development having final heights in excess of 250 m), requires that careful attention be paid to the safety and security of these facilities. In this paper, the main failure mechanisms of these sand tailings dams that have generated incidents of different magnitude involving loss of human life, significant environmental damage, and economic losses are described. Some key characteristics of reported incidents in Chile are presented, including failures resulting from the mega-earthquake that occurred on 27 February 2010 (Maule Region, Chile). Finally, the engineering practice and present Chilean regulatory framework, which have allowed progressive improvements in the construction, operation, and closure of such deposits, are described.

Key words: sand tailings dams, earthquakes, liquefaction, slope instability.

Résumé : Le Chili est un des premiers producteurs de cuivre du monde. Ce pays est situé dans une zone géographique où de nombreux tremblements de terre de forte magnitude se produisent régulièrement, ce qui nécessite de porter une attention particulière à la sécurité et à la fiabilité des barrages de résidus miniers qui du fait de la croissance actuelle de l'industrie du cuivre sont de plus en plus importants et hauts (certains peuvent atteindre jusqu'à 250 m de hauteur). Dans cet article, les principaux mécanismes de rupture de ces barrages ayant entrainés des pertes humaines, des dommages environnementaux et économiques, sont présentés. Des détails sur les incidents répertoriés au Chili sur ces ouvrages sont décrits et notamment ceux concernant le tremblement de terre exceptionnel qui s'est déroulé le 27 février 2010 dans la région de Maule. Finalement, nous présentons le cadre réglementaire chilien actuel et les pratiques d'ingénieries mises en place en vue d'améliorer progressivement la construction, le fonctionnement opérationnel et la fermeture de ces ouvrages.

Mots-clés : barrages de résidus miniers, tremblements de terre, liquéfaction, stabilité de pente.

Introduction

During recent years, the Chilean mining industry has experienced a significant increase in the production of metallic and nonmetallic minerals, becoming one of the main copper producers in the world. According to recent projections, during the next 8 years copper production will increase by more than 30% with respect to 2013 (Solminihac 2013). Considering that currently the mineral grade of the deposits is typically 1.0%, nearly 99% of the processed material becomes mining residues (tailings, heap leach waste, slag). Tailings currently generated in Chile represent approximately 1 000 000 t/day, being the total of residues produced by processing plants. Historically, from an economic point of view, the most common and efficient solution to store the residues produced by the flotation process has been the construction of deposits using these same residues as the retaining dyke and embankments.

Tailings dams are the most common type of deposits of mining residues in Chile, and represent the highest risk in terms of mechanical instability. In the event of a failure or collapse, the tailings in such dams may be released through a breach in the retaining embankment. The result is similar to a landslide, with the consequences often being the rapid release of large amounts of saturated, viscous tailings (see Blight 1997).

Considering the total incidents reported worldwide in mining deposits (from 1901 to 2013), 41% (118 cases) occurred in tailings dams constructed using tailings and (or) cyclone sand tailings (sand tailings dams). The main causes of failure or collapse were earthquakes, overtopping, seepage, and foundation instability. (ICOLD 2001; Troncoso 2002; Rico et al. 2008; Azam and Li 2010; Ramírez 2010; WISE Uranium Project 2013 last updated 18 December 2012).

In Chile, failures have mainly occurred due to seismic liquefaction with flow failure, followed in order of occurrence by slope instability with seismically induced deformations and, in some cases, overtopping (Dobry and Alvarez 1967; Castro and Troncoso 1989; Troncoso et al. 1993). These failures have mainly been in operational sand tailings dams constructed using the "upstream" method, located in areas with an average rainfall regime, including Valparaíso, Santiago, Rancagua (central zones), and Maule (southern-central), (ICOLD 2001; Troncoso 2002; Carvajal and Pacheco 2005; GEER 2010). The Barahona (1928), El Cobre (1965), and Las Palmas (2010) cases represent only a sample of the catastrophes that have resulted as a consequence of inadequate mechanical performance during seismic events, leading to structural failure or collapse of sand tailings dams.

In this paper, an update of the incidents recorded in sand tailings dams in Chile is presented, identifying the associated causes. A series of cases is presented, including the effects of the mega-earthquake of 27 February 2010 (Maule Region, Chile), assessing the most frequent failure mechanisms. The paper then presents the development of engineering practice and the evolving Chilean regulatory framework, which has allowed the development of sand tailings dams projects of the order of 250 m high, whilst

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G. Villavicencio, R. Espinace, J. Palma, and P. Valenzuela. Grupo de Geotecnia, Escuela de Ingeniería en Construcción, Pontificia Universidad Católica de Valparaíso, Avenida Brasil 2147, Valparaíso, Chile.
A. Fourie. School of Civil and Resource Engineering, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia.
Corresponding author: Gabriel Villavicencio (e-mail: gabriel.villavicencio@ucv.cl).

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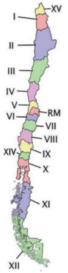
Table 1. Existing tailings dams in Chile (data from SERNAGEOMIN 2012).



			Tailings dams		
Zone	Key	Region name (Chile)	Operational	Inactive	Total
Northern	XV	Arica and Parinacota	0	0	0
	I	Tarapacá	1	0	1
	II	Antofagasta	13	8	21
	III	Atacama	45	72	117
	IV	Coquimbo	39	166	205
Central	RM	Metropolitana, Valparaíso, and Rancagua	24	75	99
Southern	VII and XI	Maule and Aysén	3	3	6

ensuring satisfactory mechanical stability. This is a particularly significant issue in Chile, given the need to prevent the negative effects that a failure or collapse of such deposits may impose on the population and productive agricultural activities, both of which are often located downstream of these tailings dams, sometimes in very steep terrain. Even in the absence of human activity, there is the ever-present need to protect the downstream environment.

Sand tailings dams in Chile

Survey and condition

In Chile a significant proportion of tailing dams are currently abandoned, which poses a critical environmental risk. The survey done in 2010 by the National Service of Geology and Mining (SERNAGEOMIN) showed the existence of 449 deposits of tailings, mainly distributed in the northern and central regions of Chile (Table 1). Approximately 70% of them are dams constructed using cyclone sand tailings, 7%, by earth fill or rock fill, and 3%, by filtered paste and thickened tailings. There is no information available regarding the remaining 20% of tailings dams, which are all essentially abandoned and already covered to some extent by vegetation. Nearly 39% of the documented sand tailings dams were in operation and 61% either abandoned or in the process of being closed (SERNAGEOMIN 2012).

In relation to mechanical stability and the risk of collapse, 9% of the sand tailings dams recorded by SERNAGEOMIN were considered to be in an unacceptable condition, 41% were acceptable, and 50% were marginal, primarily due to potential mechanical instability (liquefaction, slope instability, overtopping, etc.) or to significant contaminant emissions. In Valparaíso, where approximately a third of tailings dams in the metropolitan and central areas of Chile are concentrated, Carvajal and Pacheco (2005) established that 42% of the sand tailings dams (i.e., those constructed using cyclone underflow) were in a condition classified as "unacceptable to deficient", and 58% in a condition regarded as acceptable, in terms of their mechanical and environmental stability condition.

Failure mechanisms observed

Four causes have been established as the main factors contributing to instability of Chilean sand tailings dams: construction method, poor compaction, high fines content in the cyclone tailings sands, and an elevated degree of saturation. These causes may be attributed to inadequate design, construction, and operation, or combinations of these factors. Associated dominant failure mechanisms that have been observed are: seismic liquefaction with flow failure (true liquefaction), slope instabilities with seismically induced deformations, and overtopping.

Seismic liquefaction and flow failure

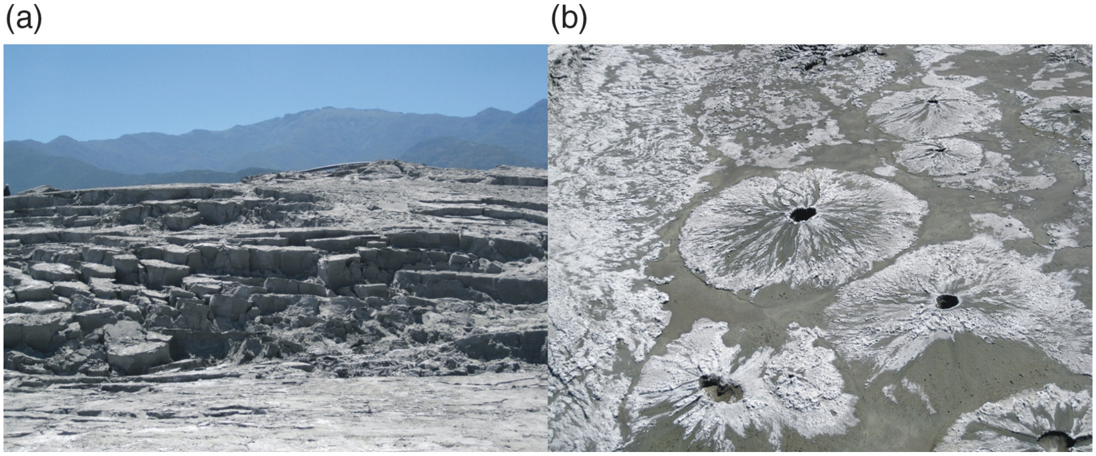
During seismic events, tailings sand dams have been shown to be very susceptible to seismic liquefaction, specifically the phenomena called flow failure or true liquefaction (Verdugo 2005). Such failures usually result from the generation of excess pore-water pressures during seismic events. These excess pore pressures cannot be dissipated quickly enough to prevent undrained loading conditions from prevailing. The effective confining pressure may be reduced to zero, or near zero, and the shear strength of the cohesionless tailings thus approaches zero. This type of failure is characterized by the short period of time that it takes, a few minutes, and by the large deformations of the tailings mass. Regarding the cases of Chilean sand tailings dams, analyses allow identification of the following contributory factors (Troncoso 1997; Blight et al. 2000; Verdugo 2011):

- Most dams were operational when earthquakes occurred and presented a "clear water" decant pond close to the crest of the retaining dyke. The presence of water was crucial in causing a rapid increase of the pore-water pressures during the application of seismic loads.
- Low density of tailings sand used for the construction of the retaining dyke due to inadequate mechanical compaction.
- Sand tailings used in the construction of retaining dykes showed a high silt content. The inadequate deposition and cycloning systems used generated low shear strength silt lenses in the downstream slope in areas close to the retaining dyke crest. These lenses facilitated the development of critical failure mechanisms.
- The upstream construction method created failures due to liquefaction of material below the retaining dyke (unconsolidated and loose tailings slimes).

Regarding the observed failure mechanisms, from the investigations carried out by Blight et al. (2000), Troncoso (2002), and the analyses done by the authors on the effects of the earthquake of 27 February 2010, it was concluded that in those dams showing partial or total liquefaction:

- The seismic inertial forces caused liquefaction of the superficial layers of fine materials.
- Liquefied tailings and the decant pond showed an oscillatory movement during and immediately after the earthquake, temporarily leaving the upstream slope of the dam unconfined. Therefore, the upstream slope, in its weakened state, slumped towards the tailings basin, generating cracks or fissures parallel to the dam crest.
- Landslide wedges were created in the downstream slope due to the combined effect of inertia forces, pressure of liquefied tailings, and decrease of basal contact areas.
- Movement of liquefied fine materials through cracks and fissures eroded the retaining dyke and generated sloughs.
- Adjacent sloughs and slumps allowed the escape of unconfined fine material, thus allowing the generation of progressive liquefaction, with large volumes of fines showing a low resistance and flow vulnerability.
- The combination of the large pressures of liquefied fines and the likely decrease of the shear strength of tailings sand may have led to failures due to landslides and flow failures.
- The gradual progress of liquefaction to greater depths within the tailings compromised the entire deposit, generating staggered

Fig. 1. Effects of the earthquake of 27 February 2010, Maule Region, Chile: (*a*) stepped terraces in an retaining dyke resulting from seismically induced liquefaction; (*b*) sand craters in tailings basin.



terraces that remained even after the earthquake (Fig. 1*a*). The evidence of liquefaction in the tailings basin was shown by the eruption of volcanoes caused by the increased pore pressures (Fig. 1*b*). Once the excess pore pressures dissipated, the structures stabilized, with a new geometry that provided less resistance (residual, post-liquefaction) than the original retaining dyke.

Slope instabilities

Even in the absence of sufficiently high excess pore pressures to trigger liquefaction, the dynamic stresses (seismic inertial forces) may still result in slope instabilities, thus significantly compromising the structural integrity and operational stability of a tailings dam. Slope instability of sand tailings dams may be generated by the following factors:

- Slopes at or close to their natural angle of repose (i.e., retaining dyke constructed by hydraulic deposition without mechanical compaction) and having substantial zones of saturated material.
- Variations of the position of the phreatic level in relation to the design value, as a consequence of intense rains, poor management of the tailings decant pond, an increase in the saturation rate by inadequate operation (e.g., inadequate time for evaporative drying and consolidation), or nonexistent or inadequate functioning of the basal drainage system.
- Presence of a low strength layer in the retaining dyke, associated with the deposition of layers of poorly cyclone tailings sands, which have a high percentage of fine particles (<80 μm).
- Decrease in shear strength of the foundation soil, or inadequate geometry of the retaining dyke (crest width, freeboard height, and slopes).

Observations have allowed identification of various failure surfaces having either a semicircular-type shape or wedge morphology (see Figs. 2*a* and 2*b*, respectively). According to studies carried out by Troncoso (1997), the failure mechanisms in tailings sand dams constructed using upstream and centerline methods usually develop sliding-wedge type failure surfaces.

During the construction and operation of a sand tailings dam, the phreatic surface may be quite elevated, as tailings are deposited in a fluid state. This means the pressure on the retaining dyke is even higher if the tailings are unconsolidated, varying in response to the depth of newly deposited tailings, as well as the time between deposition cycles, the permeability of the tailings sand, and the efficiency of underdrainage (if provided). Pore-water pressures under seismic action increase in the saturated zones of the dam, thus diminishing the resistance and increasing the driving forces.

According to Castro and Troncoso (1989) and Castro (2003), mechanical instability under seismic conditions in a tailings sand dam may be caused once the shear stresses induced by the earth tremor (τ_d) are higher than the undrained shear strength of the material (S_u) or higher than the average steady state strength (S_s). Castro (2003) defines the following features for the unstable case: (*i*) triggering strain is low for loose saturated sands (0.2% to 1.0%), (*ii*) the earthquake triggers the failure if accumulated strain reaches the triggering strain value, and (*iii*) when failure is triggered seismically, induced pore pressures may be less than 50% and the failure is typically a major slide.

Seismically induced deformations

Seismically induced deformations in sand tailings dams may cause fissures, which may significantly reduce the safety of the retaining dyke and compromise the tailings basin capacity.

In the case of excess pore pressures generated by the action of seismic loads (cyclic loading), if the sand tailings dams contain dilative material, the phenomenon called cyclic mobility may be generated (Verdugo 2005), resulting in some “strain-softening” of the material, with a progressive increase of the deformations that may affect the structural behavior of sand tailings dams. Depending on the magnitude of the deformations, the cyclic mobility can generate overtopping if deformations are greater than the freeboard height and (or) reduce the crest width of the retaining dyke.

In extreme cases, a transverse fissure from the crest to the downstream slope of the dam may lead to an uncontrolled release of the retained tailings and the collapse of the deposit. However, a dam could show significant fissures without necessarily resulting in complete release of retained tailings; it all depends on the extent of fissure development and the state and location of retained tailings, relative to the retaining dyke. Based on the authors' post-earthquake investigations of a number of tailings dams, characteristic responses have been identified, as discussed below.

Deformations under tensile stresses

Propagation of seismic waves generates tensile stresses that may exceed the material resistance. This occurs particularly in the retaining dyke crest, where the acceleration amplification is higher and the confining stresses are minimal. Resulting fissures are longitudinal and propagate downwards from the surface, usually being about 1.0 to 2.0 cm wide. This type of discontinuity does not usually represent a risk of partial or total emptying of the basin (Fig. 3).

The upper portion of a dam may also experience transverse fissures, caused by the propagation of tension waves produced by the reflection of the compressive seismic waves from the free side

Fig. 2. Slope instability: (*a*) circular-type failure surface; (*b*) landslide of slopes generated at the moment of a seismic event.

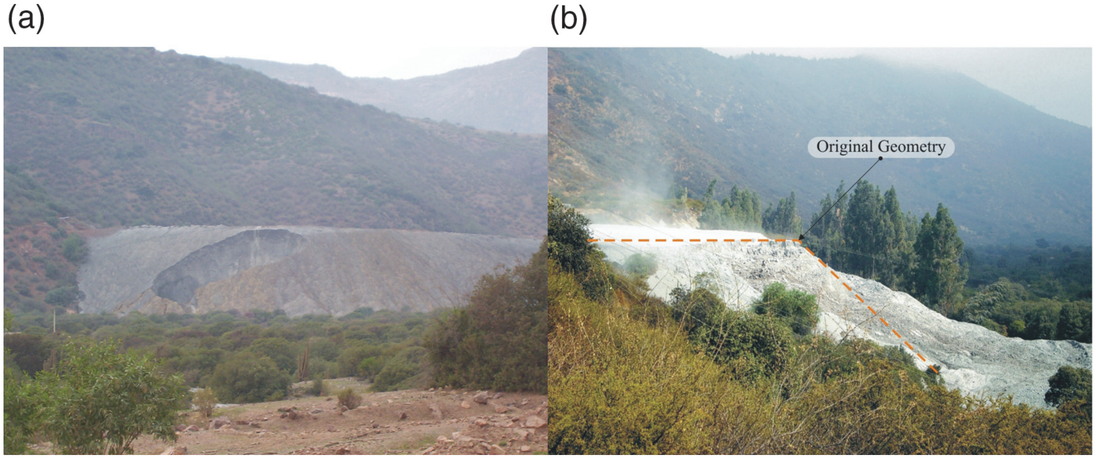


Fig. 3. Longitudinal fissures generated by tensile stresses in retaining dyke.

of the retaining dyke crest. Although such fissures only create small, shallow discontinuities, they could result in a possible rupture scenario, particularly in dams with a decant pond close to the retaining dyke and a reduced freeboard height, as their direction is perpendicular to the crest.

Deformations caused by seismic shear stresses

Slides may occur when the seismic acceleration exceeds the inertial mass of the tailings in the retaining dyke. Such slides cause 0.1 to 1 m wide fissures at the start of the fissure surface. When displacement of the unstable block is generated, a scarp in the upper zone of the failure surface is formed (Fig. 4). The magnitude of this displacement depends on the duration of the earthquake and the number of cycles during which the yield acceleration is exceeded.

Settlements of upstream slope

Settlements cause fissures in the basin, in sectors of variable tailings thickness in areas close to the retaining dyke (upstream slope). The fissures are again parallel to the crest of the dam, along with rotation and settlement of the dyke towards the basin, resulting in the emergence of discontinuities that potentially induce rupture surfaces. These types of fissures are generated mainly in sand tailings dams built by the upstream and the centerline methods.

Even more dangerous is the development of fissures due to settlement caused by the presence of slime pockets inside the retaining dyke. Such pockets result from poor construction control, which is almost inevitable in the centerline construction method, but less frequent in downstream dams. These fissures generally have a parabolic shape in plan, open towards the basin. In extreme cases, these may induce a flow and release of the retained tailings (Fig. 5).

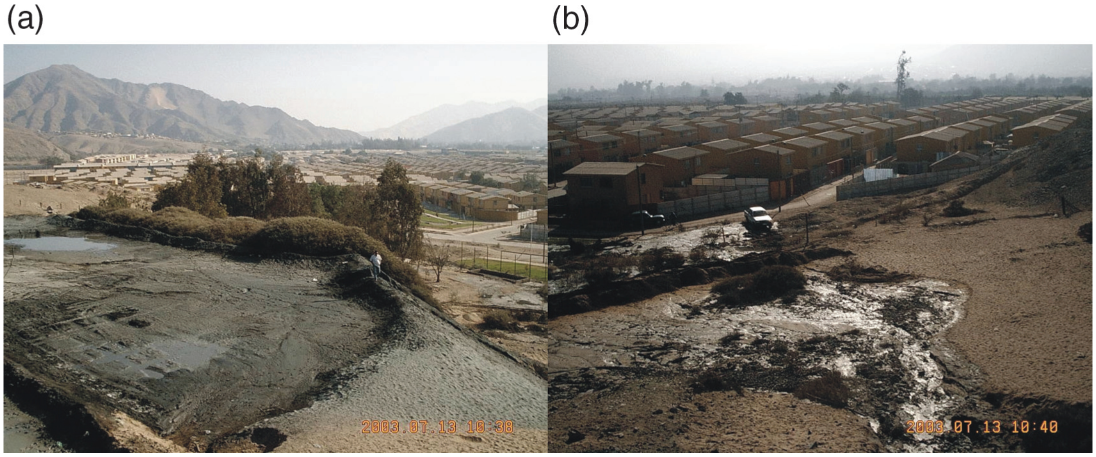
Overtopping

An excessive level of retained fine tailings in the decant pond, resulting from an extreme rainfall event or poorly controlled operation of a tailings sand dam, may result in reduced freeboard. Failure of a dam may be caused by an overflow of the ponded waters, as the level rises progressively. Ultimately, a slide surface can be produced, which may lead to progressive collapse of the dam (Figs. 6*a* and 6*b* show such overtopping, which could possibly

Fig. 4. Deformations caused by seismic shear stresses in retaining dyke resulting from the earthquake of 27 February 2010, Maule Region, Chile.

Fig. 5. Upstream slope deformations of retaining dyke caused by settling of underlying slimes.

Fig. 6. Overtopping incident: (*a*) retaining dyke and basin of the sand tailings dam; (*b*) flow failure in downstream direction.



ultimately result in loss of containment). Rapid increases of pore-water pressure due to a rise in phreatic surface associated with an overtopping event may even generate static liquefaction of the tailings (Davies et al. 2000; Fourie et al. 2001).

Failure cases reported

Since the beginning of the 20th century until the present (from 1901 to 2013), a total of 38 cases of mechanical instability of sand tailings dams in Chile caused by seismic liquefaction, slope instability with seismically induced deformations, and overtopping have been reported and (or) documented. Failures occurred as a result of earthquakes that affected the northern, central, and central-southern areas of Chile. They have been mainly of the thrust-type interplate (reverse failure in the subduction area of the Nazca and South American plate at depths lower than 40 km, e.g., 1985 and 2010 earthquakes), intermediate depth interplate (Nazca plate subducting at depths ranging between 70 and 110 km), and continental interplate in the Andes mountain range (e.g., 1965 and 1997 earthquakes), (Dobry and Alvarez 1967; Troncoso 2002; Verdugo 2011).

In relation to significant seismicity in Chile, there is a general consensus among national and international researchers of the existence of two large areas known as "seismic gaps" located in Northern Chile, between Copiapo and Illapel, and between the Regions of Arica and Parinacota and of Antofagasta. The concept of a "seismic gap" is one in which the likelihood of a large magnitude earthquake is increased because of the absence of such an event in the recent past (Comte and Pardo 1991). The two areas regarded as seismic gaps are of considerable interest, considering the quantity of tailing dams located in the designated areas (approximately 85% of the total number of tailings dams in Chile).

Analysis of available information shows failure mechanisms other than earthquakes have been recorded, such as overtopping and piping. Details of the previously mentioned 38 failures of sand tailings dams in Chile were compiled, primarily using information from databases provided by SERNAGEOMIN and information collated over many years by the Geotechnical research group at Pontificia Universidad Católica de Valparaíso (PUCV). The failures in tailings dams in Chile (Table 2) correspond to about 32% of cases reported in the world (ICOLD 2001; Troncoso 2002; Rico et al. 2008; Azam and Li 2010; Ramírez 2010; WISE Uranium Project 2013 last updated 18 December 2012). Analysis of the documented information allows the following conclusions to be drawn:

- Nearly 50% of the cases were generated by liquefaction with flow failure, 32% due to slope instability and seismically induced deformations, and 18% by overtopping with flow failure.
- The mechanical instability cases developed mainly in sand tailings dams constructed using the upstream method, with a retaining dyke height less than 40 m or a storage capacity less than 50 × 10^6 m^3, usually belonging to medium-scale mining operations (copper production between 100 000 and 3 000 000 t/year, Villavicencio 2009). Of these, 53% were in operation and 47% under abandonment or closure conditions.
- The historical cases of incidents caused by the earthquakes of 1965, 1981, 1985, and 2010 in sand tailings dams from V Region, (Valparaíso, Central Chile), correspond to 68% of the total cases reported, and they present the following factors in common: construction method (upstream), poor or zero compaction, major slope inclination between 1.2:1 to 1.7:1 (V:H, where V is vertical and H is horizontal) generated by the simple hydraulic deposition of cyclone sands tailings, and (or) a high degree of saturation (caused by precipitation and (or) inadequate management of superficial and (or) subsurface waters in areas with significant precipitation).
- The cases of incidents caused by overtopping in sand tailings dams from IV, V, and VI Regions, (Vallenar, Valparaíso, and Rancagua, respectively), associated with heavy rains, exhibited loss of crest width, inadequate freeboard, and a progressive erosion of the retaining dyke, which eventually resulted in a flow failure of the stored tailings.

Some examples of failures in Chilean sand tailings dams

Three examples of failures generated by the earthquakes of 14 October 1997 (Coquimbo) and 27 February 2010 (Maule Region) are described in the following section. These particular cases were chosen because they have not been discussed in detail in the literature, and relevant information was available through the authors' files.

Earthquake on 14 October 1997

The intraplate earthquake that affected the northern zone of Chile on 14 October 1997, with an epicenter 20 km SE of Illapel (31°42.5′S, 71°28.8′W), at 33 km depth and having a magnitude (Ms) of 7.0, generated failures at the Antiguo tailings sand dam (La Cocinera Plant), which was no longer operational (considered abandoned); (30°33′5.66″S, 71°10′41.43″W). This tailings dam was built using a combination of the upstream and centerline methods, without mechanical compaction, with a final height of 30 m and downstream slope of 1:1.7 (V:H).

The earthquake occurred after an exceptional amount of rainfall in the region. The General Water Authority of the Limarí Province (IV Region of Chile) reported that during the winter of 1997, in the city of Ovalle, the rainfall was 279 mm, (the average rainfall for a regular year in the area was 101 mm). The day before the earthquake, the rainfall where the Cocinera Plant is located exceeded 20 mm.

According to information collected and analyzed, this dam had been significantly affected by earthquakes in previous years, where the most interesting case involved the large thrust observed during the 1943 earthquake with an epicenter in Illapel (Ms: 7.9), where loss of human life occurred. According to visual inspection and surveys at the time, it was concluded that the 1997 earthquake, together with the rainfall of the day before, caused liquefaction at the Antiguo sand tailings dam, generating a flow failure of nearly 60 000 m^3 of tailings for more than 150 m downstream, partially dragging lamp posts and covering most of the blanket drainage of an adjacent dam under operation (Fig. 7). The tailings slide crossed an access road, covering it to a depth of more than 10 m. The mining company decided not to conduct a study to determine the mechanical stability of the sand tailings dam post-earthquake, and therefore relevant geotechnical information was not available.

Earthquake on 27 February 2010

The interplate earthquake on 27 February 2010, having a magnitude (Mw) of 8.8 at a depth of 35 km offshore the Maule Region, represents the sixth largest earthquake recorded in the world since 1900. The rupture zone had a length of approximately 530 km by 180 km wide, in a subduction zone in which the Nazca plate passes eastward and downward beneath the South American plate (GEER 2010). This earthquake, along with the subsequent tsunami, caused significant damage in the area and the death of thousands of people.

In relation to failures in sand tailings dams developed in the zones affected by this seismic event, between the Valparaíso and Maule Regions, a total of five failure cases were recorded. The summary of the causes and consequences is presented in detail in Table 3. The following are the two incidents generated by seismic liquefaction:

Sand tailings dam Las Palmas (35°11′4.59″S, 71°45′35.82″W)

The most crucial case was the collapse of the Las Palmas sand tailings dam (COMINOR Mining), which is located in the city of Pencahue (Maule Region) at a distance from the epicenter of 133 km, resulting in liquefaction and flow failure (GEER 2010;

Table 2. Incidents in Chilean sand tailings dams.

Dam	Location (city/Region)	Incident date	Construction method	Height (m)	Slope (H:V)	State	Pondage volume (m^3)	Failure mechanism	Cause or event	Flow volume (m^3)	Flow (m)
Agua dulce	Sewell, VI Region, Rancagua	15/06/1915	—	61	—	OP	—	OT+FF	Strong rains and overflow	180 000	—
Barahona 1	Sewell, VI Region, Rancagua	01/12/1928	US	65	2:1	OP	20 000 000	LQ+FF	Earthquake Ms = 8.3, *R* ≈ 95 km	2 800 000	—
El Cerrado	Cabildo, V Region, Valparaíso	28/03/1965	US	25	1.4:1	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	—	—
El Cobre Viejo	Nogales, V Region, Valparaíso	28/03/1965	US	35	1.4:1 to 1.2:1	OP/AB	4 250 000	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	1 900 000	12 000
El Cobre Chico	Nogales, V Region, Valparaíso	28/03/1965	US	26	1.4:1 to 1.2:1	OP	985 000	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	—	—
El Cobre Nuevo	Nogales, V Region, Valparaíso	28/03/1965	DS	19	3.7:1	AB	350 000	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	350 000	12 000
Cerro Negro No. 1	Cabildo, V Region, Valparaíso	28/03/1965	US	46	1.2: 1 to 1:1	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	—	—
Cerro Negro No. 2	Cabildo, V Region, Valparaíso	28/03/1965	US	46	1.2: 1 to 1:1	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 68 km	—	—
Cerro Negro No. 3	Cabildo, V Region, Valparaíso	28/03/1965	US	20	1.2:1	OP	500 000	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 38 km	85 000	5000
Hierro Viejo	Petorca, V Region, Valparaíso	28/03/1965	US	5	1:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 63 km	800	1000
Los Maquis 1	Cabildo, V Region, Valparaíso	28/03/1965	US	15	1.7:1	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 15 km	23 000	40 000
Los Maquis 3	Cabildo, V Region, Valparaíso	28/03/1965	US	15	1.4:1	OP	43 000	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 15 km	21 000	5000
La Patagua	La Ligua, V Region, Valparaíso	28/03/1965	US	15	1:1 to 1.4:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 25 km	35 000	500
Bellavista	San Felipe, V Region, Valparaíso	28/03/1965	US	20	1.7:1 to 1.4:1	OP	450 000	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 55 km	70 000	800
El Sauce 1	Llay Lay, V Region, Valparaíso	28/03/1965	US	6	1.7:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 66 km	—	—
El Sauce 2	Llay Lay, V Region, Valparaíso	28/03/1965	US	5	—	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 66 km	—	—
El Sauce 3	Llay Lay, V Region, Valparaíso	28/03/1965	US	5	—	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 66 km	—	—
El Sauce 4	Llay Lay, V Region, Valparaíso	28/03/1965	US	5	—	AB	—	SI+SID	Intraplate earthquake Ms = 7.4, *R* ≈ 66 km	—	—
Ramayana	V Region, Valparaíso	28/03/1965	US	5	1.5:1	OP/AB	—	LQ+FF	Intraplate earthquake Ms = 7.4, *R* ≈ 85 km	156	—
Marga	Sewell, VI Region, Rancagua	1980	—	—	—	AB	—	OT+FF	Strong rains and overflow	—	—
Arena	Sewell, VI Region, Rancagua	1980	—	—	—	AB	—	OT+FF	Strong rains and overflow	—	—
Veta del Agua No. 2	Nogales, V Region, Valparaíso	07/11/1981	US	20	1.2:1	OP	—	LQ+FF	Intraplate earthquake Ms = 6.5, *R* ≈ 85 km	—	—
Vallenar N° 1 y No. 2	Vallenar, IV Region, Vallenar	1983	—	—	—	AB	—	OT +FF	Strong rains	—	—
Veta del Agua No. 1	Nogales, V Region, Valparaíso	03/03/1985	US/CL	24	1.5:1	OP	700 000	LQ+FF	Intraplate earthquake Ms = 7.8, *R* = 80 km	280 000	5000
Cerro Negro No. 4	Cabildo, V Region, Valparaíso	03/03/1985	US/CL	40	1.7:1	OP	2 000 000	LQ+FF	Intraplate earthquake Ms = 7.8, *R* = 105 km	500 000	8000
Cobre No. 4	Nogales, V Region, Valparaíso	03/03/1985	DS	50	4.6:1	AB	—	SI+SID	Intraplate earthquake Ms = 7.8	—	—
Almendro	IV Region, Vallenar	14/10/1997	US	18	1.5:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.0, *R* = 100 km	—	—
Algarrobo	IV Region, Vallenar	14/10/1997	US	20	1.5:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.0, *R* = 80 km	—	—
Maitén	IV Region, Vallenar	14/10/1997	US	15	1.5:1	OP/AB	—	LQ+FF	Intraplate earthquake Ms = 7.0, *R* = 120 km	—	—
Tranque Antiguo Planta La Cocinera	Vallenar, IV Region, Vallenar	14/10/1997	US/CL	30	1.7:1	OP	—	LQ+FF	Intraplate earthquake Ms = 7.0, *R* = 80 km	60 000	—
El Cobre 2, 3, 4 y 5	Nogales, V Region, Valparaíso	22/09/2002	US	—	—	AB	—	OT+FF	Strong rains and overflow	8000	—
El Cobre	Nogales, V Region, Valparaíso	08/11/2002	US	—	—	AB	—	OT+FF	Strong rains and overflow	4500	—
Cerro Negro No. 2	Cabildo, V Region, Valparaíso	03/10/2003	US	—	—	OP	—	OT+FF	—	80 000	—
Tranque Adosado Planta Alhué	Alhué, Region Metropolitana	27/02/2010	DS	15	4.5:1	OP	—	LQ+SI	Intraplate earthquake Mw = 8.8, *R* = 252 km	—	—
Las Palmas	Pencahue, VII Region, Maule	27/02/2010	—	15	—	AB	—	LQ+FF	Intraplate earthquake Mw = 8.8	80% of total volume	500
Tranque Planta Chacón	Cachapoal, VI Region, Rancagua	27/02/2010	—	—	1.8:1	AB	—	SI+SID	Intraplate earthquake Mw = 8.8	—	—
Veta del Agua Tranque No. 5	Nogales, V Region, Valparaíso	27/02/2010	US	—	1.4:1	AB	—	SI+SID	Intraplate earthquake Mw = 8.8	80 000	100
Tranque No. 1 (Minera Clarita)	San Felipe, V Region, Valparaíso	27/02/2010	US	—	1.2:1	AB	—	SI+SID	Intraplate earthquake Mw = 8.8	80% of total volume	—

Note: H, horizontal; V, vertical; US, upstream; UP/CL, upstream and centerline; DS, downstream; OP, operational stage; AB, abandonment; OP/AB, end of operational stage; LQ+FF, liquefaction with flow failure; SI+SID, slope instability with seismically induced deformations; OT+FF, overtopping with flow failure; *R*, epicentral distance.

Fig. 7. Antiguo sand tailings dam at La Cocinera Plant, where slides and deformations were caused by the earthquake of 14 October 1997.

Ramirez 2010; Verdugo 2011). Figure 8 shows the general condition of the tailings dam after the collapse, with flow clearly evident. The distance of travel of the tailings was approximately 500 m. The collapse caused the death of four people inhabiting a nearby home, and generated an obstruction of the Los Ladrones and Las Palmas streams.

This sand tailings dam was closed in 1997 and included a clayey soil cover over its entire surface. However, a failure due to seismic liquefaction was observed to occur at the base level of the retaining dyke, apparently due to saturation of the lower few meters (0.5 to 1 m) produced by undetected groundwater. This zone of saturation was apparently not detected at the time of closure of the deposit. Figure 9 clearly shows groundwater seeping from a hill slope adjacent to the Las Palmas tailings dam, days after the failure occurred.

Sand tailings dam Adosado (34° 2′26.04″S, 71° 1′50.97″W)

Another case of liquefaction is the sand tailings dam Adosado (Alhué Plant, Florida Mining), located in Alhué (Maule Region), 271 km from the epicenter. The dam was built using the downstream method with cyclone sand tailings (25% of particles below 80 μm), but with poor mechanical compaction. The retaining dyke had a height of 8 to 13 m and a 1:4.5 (V:H) slope.

According to studies conducted by the company Geotecnia Ambiebtal LTDA in December 2009, this sand tailings dam had a high seismic liquefaction potential due to the following factors:

- *Degree of saturation of the retaining dyke* — The retaining dyke had a high degree of saturation, due to seepage from the stored tailings, proximity of the “clear water” decant pond and due to the sprinkler system used as a mitigation measure for preventing wind erosion (Fig. 10). Piezometers installed at points close to the top of the dyke in the downstream slope indicated that the phreatic surface was between 6 to 7.5 m below the tailings surface.
- *Penetration resistance and state of compaction* — Based on dynamic cone penetration tests (DCPT) and variable energy lightweight dynamic cone penetrometer (PANDA) tests (Villavicencio 2009; Villavicencio et al. 2011; Espinace et al. 2013), the sand tailing dams gave the following values:

- From 0.0 to 7.0 m, the dynamic cone penetration test index (NDCPT) obtained from the DCPT test was lower than 10 (blows per 30 cm) and the pseudo-static resistance tip (q_{d}) was lower than 3 MPa, according to the PANDA tests.
- Given these values, the state of compaction of the sand tailings was classified as very low to low (relative density < 45%), with a high likelihood of exhibiting contractive behavior and a high to very high liquefaction potential according to the correlations proposed by Espinace et al. (2013).

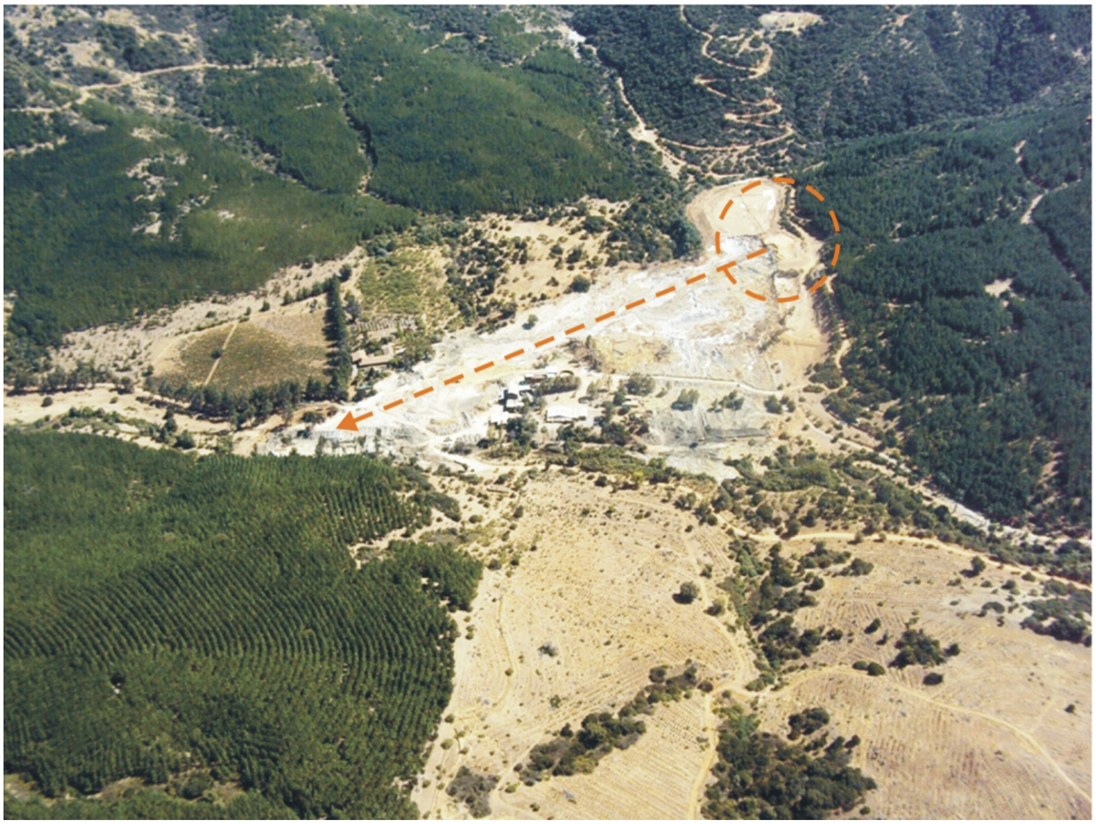
Under this critical scenario, trenches were excavated in the retaining dyke to generate rapid drainage, dissipate the pore-water pressures, and lower the phreatic surface, thus minimizing further liquefaction potential. The 27 February 2010 earthquake generated a maximum effective acceleration ($a_{\max}$) of 0.34g, causing the liquefaction of the sand tailings dam (Fig. 11). It is believed that the measures adopted prior to the earthquake prevented a catastrophic flow failure from occurring.

According to Verdugo (2011), the large sand tailings dams located in the central and south central regions (i.e., Las Tórtolas, Torito, Quillayes, Ovejería, etc.) exhibited acceptable mechanical behavior during the earthquake of February 2010. Moreover, the sand tailings dam “The Mauro”, currently 150 m high (projected to eventually reach 248 m), did not show any damage during the seismic event according to the evidence provided by Geotecnia Ambiental LTDA, the company that monitors this deposit every three months, and has done so for the past 4 years. Table 4 presents a summary of some characteristics of these sands tailings dams. Eyewitness reports indicate that the tailings in the basin of the deposits of some of these facilities liquefied during this event, with “waves” of tailings clearly evident. The satisfactory performance of the sand tailings dams mentioned above is testament to the ability of the mining industry to construct and operate sand tailings dams in a highly seismic region, as long as correct methodologies for construction, operation, and monitoring are followed.

Table 3. Causes and consequences of incidents reported and documented in collapsed sand tailings dams during the February 2010 earthquake.

Company/Dam	Location	State	Causes	Consequences
Cía. Minera Chilena Rumana. Tranque Planta Chacón	Chancón Town, VI Region, Rancagua Epicentral distance 281 km	Old dam, nonoperational adjacent to a new tailings dam	Insufficient compaction of the retaining dyke; external slope angle of the retaining dyke > 1:1.8 (V:H)	Longitudinal fissure, sedimentation, and landslide of the retaining dyke; collapse caused reduction of the available storage volume of the basin of adjacent tailings; slope instability with seismically induced deformations.
Cía. Minera Clarita. Tranque No. 1 Panta Bellavista	El Asiento Area, San Felipe, V Region,Valparaíso Epicentral distance 415 km	Under operation until 2009, subsequently halted indefinitely.	Insufficient compaction of the retaining dyke; external slope angle of the retaining dyke > 1:1.2 (V:H); upstream construction method	Collapse caused a great volume of tailings material to move downstream direction, flooding Tranque No. 2 out of operation; slope instability with seismically induced deformations
Tranque de Relaves Veta del Agua No. 5	Nogales Town, El Melón Sector, Quillota, V Region, Valparaíso Epicentral distance 400 km	Out of operation since 1998	Insufficient compaction of the retaining dyke; external slope angle of the retaining dyke > 1:1.4 (V:H); upstream construction method	Collapse caused the obstruction with tailings of an adjacent brook, parallel to the tailings dams for a length of the order of 100 m; slope instability with seismically induced deformations
Minera Florida, Planta Alhué Tranque de Relaves Adosado	Alhué City, Region Metropolitana. Epicentral distance 271 km	Under operation	Insufficient compaction of the retaining dyke; saturation on sand dyke areas due to insufficient drainage system; retaining dyke with a high percentage of fines (<80 μm); excessive external slope angle of the external retaining dyke	Rotational failures located along the retaining dyke; differential slide and settlement along the external slope and in areas of the inner slope of the retaining dyke; liquefaction evidence in slime and basal area of the retaining dyke; tailing runoff in sectors of the retaining dyke
Minera COMINOR. Tranque Las Palmas	Pencahue City, VII Region, Maule Epicentral distance 133 km	Nonoperational since 1997, covered by a clayey material layer	Seismic liquefaction at the basal level of the retaining dyke and the tailings basin, due to saturation (0.5 to 1 m) generated by undetected seepage, which probably emerged after completion of closure	Collapse due to liquefaction caused the death of four people inhabiting a nearby facility, however, the starter dyke reduced the flow volume; obstruction with tailings of the Los Ladrones and Las Palmas streams; tailing dispersion to nearby private lands

Fig. 8. Las Palmas sand tailings dam after the collapse generated by the 27 February 2010 earthquake.



Chilean regulatory framework and engineering practice

Chilean regulatory framework

During the past 40 years, Chile has promulgated two regulations governing the design, construction, and operation of tailings deposits. The first is the Supreme Decree No. 86 of 1970, effective until December 2006. In 2007 the second Supreme Decree No. 248 of 2007 came into force. This currently governs the design, construction, operation, and closure of tailings deposits.

Supreme Decree No. 86 of 1970

The collapse of sand tailings dams of the El Cobre mine caused by liquefaction due to the 28 March 1965 earthquake provoked a re-assessment of the methods used up to that date for the construction of retaining dykes. As a first reaction, during 1970, the authorities and the mining industry decided to not use sand tailings dams. As an alternative, they chose embankment dams constructed using borrow materials. In this way, they built the following tailings dams: Colihues, some 83 m high (CODELCO, Division El Teniente), El Indio, 74 m high (Cia Minera, El Indio), and Los Leones, 160 m high (CODELCO, Division Andina), (Barrera et al. 2011). However, the costs associated with this alternative prevented widespread adoption of the technique.

Sand tailings dams were clearly still the most economical construction method, but they needed to be safely constructed and operated to prevent failures of the type that occurred in 1965. A better understanding of the mechanical behavior of sand tailings, technical specifications, construction recommendations, and necessary monitoring and controls to ensure adequate mechanical performance were included in the Supreme Decree No. 86 of 1970: *"Reglamento de Construcción y Operación de Tranques de Relaves"* (Regulations for the construction and operation of tailing dams) of the Ministry of Mines. Such regulation, executed at a time when the discipline of geotechnical engineering was just developing in Chile, contributed significantly to improvements in the standards of design and construction of these types of structures. According to Barrera et al. (2011), in the Supreme Decree No. 86 of 1970, the following geotechnical aspects were considered:

- The design of tailings dams must follow the principles of soil mechanics and foundation engineering.
- Downstream or centerline construction methods are required.
- Compaction requirements were specified, including the uniformity and thickness of tailings layers, and the density and water content based on the Proctor compaction test. A minimum construction density was required for the sand tailings according to the specifications of the State Mining Service.
- The degree of compaction and the grain size of the deposited tailings sands must be controlled.
- Avoid saturation of the tailings sand, requiring a base drainage system, permeable sand, and control of the piezometric levels in the dam.
- Management of the tailings pond far from the crest and ensuring an appropriate freeboard.
- A minimum factor of safety of 1.20 was established for pseudostatic analyses that consider a seismic coefficient based on the population located downstream of the impoundment and within a buffer zone called "the dangerous distance".
- The concept of dangerous distance was introduced to determine the downstream trajectory and distance that the sand tailing dams could travel in the case of flow fail due to seismic liquefaction.

Despite the above requirements, a percentage of tailings dams remained with important deficiencies. This was particularly true during the operational phase, as the construction of dams using the upstream method was still permitted, (subject to approval by

Fig. 9. Groundwater flow through the retaining dyke that collapsed at Las Palmas Dam.

special resolution only), and there was often inadequate quality control during the operational phase. Therefore, although the 1965 event resulted in improved practices, deficiencies remained and the real lessons provided by the failure were not completely absorbed. Examples of this are the reported incidents generated during the earthquakes of 1981, 1985, and 1997, in the central (Valparaiso) and north-central (Vallenar) regions, as presented in Table 2.

Supreme Decree No. 248 of 2007

On 11 April 2007, the new Supreme Decree No. 248 of 2007 *"Reglamento para la Aprobación de Proyectos de Diseño, Construcción, Operación y Cierre de los Depósitos de Relaves"* (Regulations for the approval of projects for the design, construction, operation, and closure of tailings deposits) was promulgated, which represented a series of new requirements that improved both the design and operation of such structures. The new geotechnical requirements were

- Downstream and centerline construction methods are allowed. The upstream method is strictly prohibited.
- Define a degree of compaction based on the Proctor test (standard or modified), associated with the compaction method used for the construction of the retaining dyke of sand tailings.
- The sand tailings must have a fines percentage (<80 μm) less than 20%.
- Geotechnical design parameters associated with tailings sands to be used for the construction of the retaining dyke are to be defined (including shear strength, compressibility, permeability, grain size, unit weight, specific gravity, and plasticity).
- A freeboard (>2 m) and crest width (>1 m) must be ensured.
- The retaining dyke must have an underlying drainage system.

Fig. 10. Retaining dyke saturation caused by elevated water table and irrigation (sand tailings dam Adosado).

Fig. 11. Final situation after liquefaction of sand tailings dam, resulting from the earthquake of 27 February 2010, Maule Region, Chile.

- The "clear water" decant pond must be located as far as possible from the retaining dyke.
- Monitoring of the structural and hydraulic behavior of the dam is required, including pore pressure, water level, displacement, settlement, seepage, seismic accelerations, and other aspects recommended by the engineer in charge.
- Stability analyses for the tailings dam are required for the operational and closure phases, considering four calculation considerations (static stability, pseudo-static, dynamic analysis, and closure condition). Applicability of these analyses depends on the height of the tailings deposit (less or more than 15 m) and the safety factor should always be greater than 1.2. In addition, the dangerous distance must be determined.

Despite the above improvements, the Supreme Decree No. 248 of 2007 included relatively little detail on relevant geotechnical requirements.

Future regulation

In January 2009, the Law project on Mining Work Closures was introduced to the Chilean Congress; this law sought the prevention, minimization, and (or) control of the negative risks and effects of operations on the environment and human health and to ensure public safety after the closure of such facilities. Furthermore, Chile is currently working on the Bill of Mining Environmental Liabilities (MEL), which includes sand tailings dams. This bill will apply to abandoned or temporarily halted mining works that pose a significant risk to health or the environment, and aims to establish a basis for the control and reduction of all existing significant risks.

Geotechnical criteria used to reduce mechanical instability risk

In general, the following aspects are considered in the regulations (Supreme Decree No. 248 of 2007) and geotechnical criteria used in Chile (Barrera and Lara 1998; Alarcón and Barrera 2003; Barrera et al. 2011) to reduce the risk of mechanical instability of sand tailings dams:

- Use of downstream or centerline construction methods;
- Definition of a proper geometry of the retaining dyke, considering the downstream slope angle, crest width, and freeboard height. The downstream slope angle varies between 3:1 to 6:1 (V:H), depending on the particle size, specific weight, deposition area, and concentration of the discharge of the tailings sand.
- Deposition of tailings sands on the downstream slope with a certain grading, limiting the percentage of fine particles (<80 μm) to less than 20% of the dry mass. For the compaction of the retaining dyke, to define a compaction level that ensures a structure having adequate shear strength and liquefaction resistance;
- Use of tailings sands for the construction of the retaining dyke having a permeability at least 100 times that of the tailings slimes. The range of permeability for tailings sand with 20% fines is from 10^{-5} to 10^{-6} m/s (Barrera and Lara 1998).
- Construction of efficient drainage systems, able to rapidly evacuate water coming from the tailings basin;
- Movement of the clarification lagoon away from the retaining dyke, and identify areas of low permeability. These actions will

reduce leakage from the "clear water" decant pond to the retaining dyke and avoid a rise of the phreatic surface in the retaining dyke.

- Implementation and monitoring of geotechnical and environmental controls during the operational phase of the facility.

Geotechnical control of quality and monitoring

The main factors to be considered for the geotechnical control of sand tailings dams are associated with the deposition properties and parameters, deposit geometry, water presence, and sand deposition types. Such factors are described as follows.

Retaining dyke geometry

The aspects associated with the geometry of a tailings dam involve height, upstream and downstream slope angle, freeboard height, and crest width and inclination. Consequently, quarterly topographic surveys are carried out.

Phreatic level and subsurface water monitoring

The water level inside the retaining dyke plays a critical role in the seismic stability of the deposit, as the saturation of such materials poses a significant risk of liquefaction and mechanical instability. The monitoring of the position of the phreatic level has to be done through the installation of piezometers in the dyke perimeter. To monitor the subsurface waters, the position of the decant pond inside the basin must be established, along with the location of the phreatic surface and confirmation that drains are functioning satisfactorily.

Deposition of tailings sands

The main aspects to be controlled in the deposition of sands correspond to the grading and compaction density resulting from the construction method used.

- *Grading* — Current engineering practice recommends the deposition of sands for the construction of the retaining dyke with a percentage of fines between 10% and 25%. The latter depends on a balance between the geotechnical properties of the materials and the costs associated with the cyclone station process.
- *Compaction specification* — Current engineering practice considers as acceptable a compaction density of 95% SPMDD (standard Proctor maximum dry density) for structures or landfills where certain levels of deformation are acceptable, such as tailings dams. Research done by Verdugo (1997) showed for tailing sands with a fines percentage (<80 μm) ranging between 10% and 25%, that a compaction specification of 95% SPMDD is equivalent to a relative density (RD), of the order of 60% to 65%. However, in some cases, such as tailings dams from the large-scale copper mining industry, depending on the geometric configuration of the deposit and the storage volume capacity, the specified compaction rate may exceed the 95% SPMDD or a 70% RD.
- To control the compaction of each layer of tailings sand, in Chile the following standardized tests are used: sand cone method, nuclear densitometer, and light dynamic penetration tests (i.e PANDA test, utility dynamic cone penetrometer (DCP), etc.).

In-depth quality measurement

In Chile, penetration testing programmes are carried out to measure the quality variation with depth within the retaining dyke of a sand tailings dam. Thus, it is possible to estimate the compaction rate, the homogeneity of the structure resulting from the construction process, specifically the layer thickness, identify any areas of low resistance, and estimate in situ the geotechnical parameters that determine the mechanical performance of these structures. These penetration tests may utilize a range of techniques, including standard penetration test (SPT), dynamic cone penetration test (DCPT), and variable energy lightweight dynamic cone

Table 4. General characteristics of large sand tailings dams unaffected by the 27 February 2010 earthquake.

				Retaining dyke							
						Material					
Sand tailings dam	Mine	Design period	State	Slope downstream (V:H)	Final Height (m)	Type	% fines (<80 μm)	Average grain size, D_{50} (mm)	In situ density (g/cm³)	In situ moisture (%)	Compaction
Las Tórtolas	Los Bronces	1983 to 1990	Operational since 1992	1:4.0	190	Cycloned tailings sand	12–26	0.70–0.73	1.69–1.70	8–12	Mechanical
Torito	El Soldado	1985 to 1991	Operational since 1992	1:4.5	125	Cycloned tailings sand	15–20	0.70	1.63–1.66	7–10	Mechanical
Quillayes	Los Pelambres	1996 to 1998	Operated from 1999 to 2008	1:4.0	198	Cycloned tailings sand	13–18	0.75	1.60–1.62	8–11	Mechanical
Ovejería	Andina	1989 to 1999	Operational since 2001	1:4.0	120	Cycloned tailings sand	12–15	0.85	—	—	Mechanical
El Mauro	Los Pelambres	2003 to 2006	Operational since 2009	1:4.0	248	Cycloned tailings sand	13–18	0.75	1.75–1.82	9.8–12.9	Mechanical

Table 5. Comparison of the construction, operation, and control requirements for tailing dams: Supreme Decrees No. 86 of 1970 and No. 248 of 2007, and engineering practice.

Components	Specifications	DS No. 86 of 1970	DS No. 248 of 2007	Engineering practice
Retaining dyke	Geometry	No specifications	Minimum crest: 2.0 (m); minimum freeboard: 1.0 (m)	Minimum crest width: 5.0 (m); minimum freeboard: 2.0 (m)
	Construction method	Downstream; centreline; does not clearly prohibit the upstream method	Downstream; centerline; upstream methods is specifically prohibited	Downstream; centerline
	Deposition of tailings sands	Deposition towards the exterior of the dam and over the surface of the downstream slope, uniformly extended and, in specific cases, compacting in layers not exceeding 30 cm, with a water content close to the Proctor until reaching a percentage higher than the limit established through the resolution of the SERNAGEOMIN director	No specifications	Discharge generally from the crest of the dyke of the dam
	Controls	Periodic controls of the compaction rate at 1/3 and 2/3 of height in the downstream slope of the retaining dyke with no less than a monthly determination per each 100 m of length; monthly grading controls	Sands with a fine percentage (80 μm) ≤ 20%; compaction rate must be referred to the Standard or Modified Proctor test; minimum compaction is not specified; criteria to define the number and location of compaction control spots are not defined; quarterly delivery of control reports for compaction	Sands with a maximum fine percentage (80 μm) between 10% and 25%; 95% Proctor (standard or modified) or a 60% to 70% relative density (RD); topographic control of the geometry of the embankment wall (downstream slope, freeboard height and crest width); dynamic penetration assays
	Monitoring	No specifications	Monitoring of pore pressures, piezometric levels, landslides, deformations vertical and horizontal, filtrations and seismic accelerations is required.	Piezometric levels; minimum accelerations; mechanical performance (inclinometer, load cells, etc.)
Starter dyke	Geometry	No specifications	Height equal to 1/10 of the final height of the retaining dyke, with a minimum of 2 m of height	Minimum requirements as per regulations
	Lining system	No specifications	In crest and "upstream" slope	In crest and "upstream" slope
Operation	Decant water pond	Clear water will remain as far as possible from the horizontal projection of the perimeter line in the most significant allowance area of the retaining dyke.	Clear water will remain as far as possible from the retaining dyke	Clear water will remain as far as possible from the retaining dyke
Infiltration control	Retaining dyke	Basal drainage system.	Basal drainage system	Basal drainage system
	Basin	No specifications	Permeability reduction required	No specifications

penetrometer PANDA (Villavicencio 2009; Villavicencio et al. 2011; Espinace et al. 2013).

Seismic monitoring

Regarding tailings dams from the large-scale mining sector, seismic monitoring of the embankment and the deposition area is common, using accelerometers to record the generated accelerations and thus assess the mechanical performance.

It is important to point out that independent of the geotechnical controls to be carried out, the personnel in charge of the operation of the deposit should be able to develop, adapt, and update the construction procedures to secure the proper mechanical performance of the sand tailings dam according to the design specifications, the requirements of the regulating institution, and the regulations in force.

Table 5 shows a comparative analysis of the construction, operation, monitoring, and control requirements for tailings dams recommended over the last 40 years according to accepted engineering practice as well as that established by the Supreme Decrees No. 86 of 1970 and No. 248 of 2007.

Conclusions

This paper discusses a total of 38 sand tailings dams failures that have occurred in Chile, which correspond to about 32% of the total incidents reported worldwide during the period of interest. The primary cause of failures has been significant seismic activity in the country, which contrasts with most other regions of the world, where seismically induced failure has been a somewhat secondary consideration (e.g., Rico et al. 2008). Regarding the associated mechanisms, nearly 50% of the cases developed by liquefaction with flow failure, 32% due to slope instability and seismically induced deformations, and 18% due to overtopping with flow failure. These mechanical instability cases mainly developed in sand tailings dams constructed using the upstream method, with a height of the retaining dyke less than 40 m, under operational conditions (53%) or abandonment (47%) and associated with the medium-scale mining industry in Chile. This was confirmed by the 27 February 2010 earthquake (magnitude Mw = 8.8), where five cases of tailings dam failures were reported, all of which were part of the medium-scale mining industry.

The survey carried out in 2012 by the National Service of Geology and Mining identified the existence of 314 sand tailings dams, mainly distributed within the northern and central regions of Chile, of which 69% are currently considered abandoned and 31% are operational. The Geotechnical Group from the Pontificia Universidad Católica de Valparaíso established that out of the total deposits existing in the V Region of Chile, 9% are in an unacceptable condition, 41% are acceptable, and 50% are marginal, when evaluated in terms of their risk of mechanical instability (liquefaction, slope instability, overtopping, etc.) or significant contamination emission potential.

From the experiences and understandings gained from the historical failures of sand tailings dams in Chile, significant engineering progress has been possible, along with the enactment of regulations for the design, construction, operation, and closure of these types of deposits, to achieve better mechanical performance during the operational and post-closure stages. Within the main aspects considered, geometric recommendations (slopes, crest width, and freeboard height), basal drainage construction, management of the decant pond, characteristics of the tailing sands to be used in the construction of the retaining dyke (grading, compaction rate, permeability, etc.), and control and monitoring during the operational and closure phase are considered critical. An example of the results of this experience is the successful seismic performance of large dams with retaining dykes of tailing sands from the medium- and large-scale copper mining industry during the March 1985 (magnitude Ms = 7.8) and February 2010 (magnitude Mw = 8.8) earthquakes (i.e., Cauquenes, Ovejería, Las Tórtolas, Torito, Quillayes, and El Mauro).

Through one of the main regulatory bodies in Chile (i.e., regulation Supreme Decree No. 248 of 2007) a series of new requirements were implemented to improve the design criteria, the operational control, and monitoring of sand tailings dams. In particular, compaction control (in situ density and percentage of fines <80 μm) and degree of saturation represent two of the processes still requiring improved implementation, being the greatest causes of the most significant failures. There remains inadequate application of specific regulations controlling the deposition, compaction, and testing processes through standardized methodologies allowing improved quality control, and a lack of adequate control tools to assess the fundamental aspects of mechanical stability of these particular structures.

The continuous improvements to engineering practice (i.e., Alarcón and Barrera 2003; Barrera et al. 2011) and the enforcement of regulations specifically associated with the construction, compaction control, and performance monitoring (via instrumentation, visual inspections, in situ quality control testing using penetration, and geophysical tests, etc.) in operational tailings dams allow the development of structures with acceptable mechanical performance. This is true even under the action of forces generated by large magnitude seismic events, such as the mega-earthquakes that may occur in the "seismic gaps" located in northern Chile, between Copiapo and Illapel and between Arica–Parinacota and Antofagasta.

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