Exposure and Susceptibility of Inactive and Abandoned Tailings to Flash Floods in Chile

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ABSTRACT

The 2020 Global Industry Standard on Tailings Management exemplifies the move to reduce risks posed by tailings worldwide. However, inadequate attention focuses on various non-active tailings, which may ultimately become the responsibility of national or state regulators. This challenge is particularly evident in Chile, which hosts 467 inactive and 173 abandoned tailings according to Chile's National Geology and Mining Service (SERNAGEOMIN).

The two drivers of tailings failures globally are heavy precipitation and seismic activity. In Chile, from 1915 to 2010, earthquakes accounted for about 80 per cent of recorded major tailings failures, with heavy rainfall mainly responsible for the remainder. Since 2015, however, there have been several extreme rainfall and associated flash flood events in northern Chile that have mobilized tailings. Events in 2015 and 2017 have been analyzed remotely to understand the mechanisms and magnitudes of tailings erosion and mobilization.

The 24–26 March 2015 intense rainfall event most affected the Salado river basin and led to significant modification of the tailings beach at Chañaral in the Atacama Region. At least several 100 000 m^3 of tailings were scoured from the beach and transported into coastal water. Another inundation event on 11–13 May 2017 caused erosion, undercutting and partial collapse of several inactive and abandoned tailings deposits along the Marquesa river channel, which is a tributary of the Elqui river in the Coquimbo Region. The total volume of missing tailings is of the order of 100 000 m^3. These volumes are of magnitudes equivalent to those reported for some of the most significant tailings failures in Chile and highlight the urgency to systematically assess the exposure of Chile's tailings to floods, particularly in the context of changing climate and weather patterns.

INTRODUCTION

Recent high-profile failures of tailings storage facilities (TSFs), such as those in Brazil in 2015 and 2019, have catalyzed initiatives worldwide to reduce the risk posed by such events. Arguably, the most prominent and influential of these is the Global Industry Standard on Tailings Management (Global Tailings Review, 2020). Despite its progressive impact, it admits that more needs to be done to reduce the risk associated with various non-active tailings, which may become the responsibility of national or state regulators. This challenge is particularly evident in Chile; of its 757 tailings deposits, contained almost entirely within the center and north of the country, 467 are inactive and 173 abandoned according to Chile's National Geology and Mining Service (SERNAGEOMIN, 2020).

The two principal drivers of tailings failures globally are heavy precipitation and seismic activity (e.g., Rico et al., 2008; Rana et al., 2021). In Chile, from 1915 to 2010, earthquakes accounted for about 80 per cent of recorded major tailings failures (Villavicencio et al., 2014). Being one of the most seismically active mining regions of the world, Chile has logically focused on the seismic stability of its TSFs. However, many of its inactive and abandoned tailings lie in drainage systems where they are potentially highly exposed to flood events and several studies have recently drawn attention to this situation (e.g., Falcón, Herrera & Edwards, 2017; Izquierdo et al., 2020). As a contribution to defining and raising awareness of the risk of flood–tailings interaction, two case studies are presented where tailings were eroded and mobilized during the 2015 (Chañaral beach) and 2017 (Marquesa valley) extreme weather events that affected northern Chile. The aim of these studies was to estimate the magnitudes of tailings eroded and then compare them with previously documented incidents in Chile to ascertain if they were significant and what they may mean for future weather-induced failures. Estimations of the volumes of tailings eroded are based on the research of Ryder (2020), Stile (2020) and Liu (2021), which was desk based using publicly available information, as site investigations were not possible owing to travel restrictions resulting from the COVID-19 pandemic.

Chañaral beach

Chañaral beach in the Atacama Region lies immediately north of the small coastal city of Chañaral at the mouth of the Salado river (Figure 1). Between 1938 and 1974, around 150 million tonnes of untreated tailings were discharged directly into the Salado river and transported in suspension to Chañaral bay (Castilla, 1983). An artificial beach formed as a consequence, which in 1982 was about 5 km long, 0.4 km to 0.9 km wide and 1 m to 5 m deep (Castilla, 1983). From 24–26 March 2015, intense rainfall and flooding events affected the Atacama Desert (mean annual precipitation in the driest parts is less than 5 mm), with the Salado river basin being most affected: total rainfall up to 80 mm over 51 hours, flood peak discharge of about 1000 m^3/s and flood depths over 4.5 m in Chañaral (Wilcox et al., 2016). Flood water from the Salado river carved two clearly defined pathways across Chañaral beach, eroding tailings into the ocean, and deposited brown sediment on top of a large area of the beach (Figure 1).

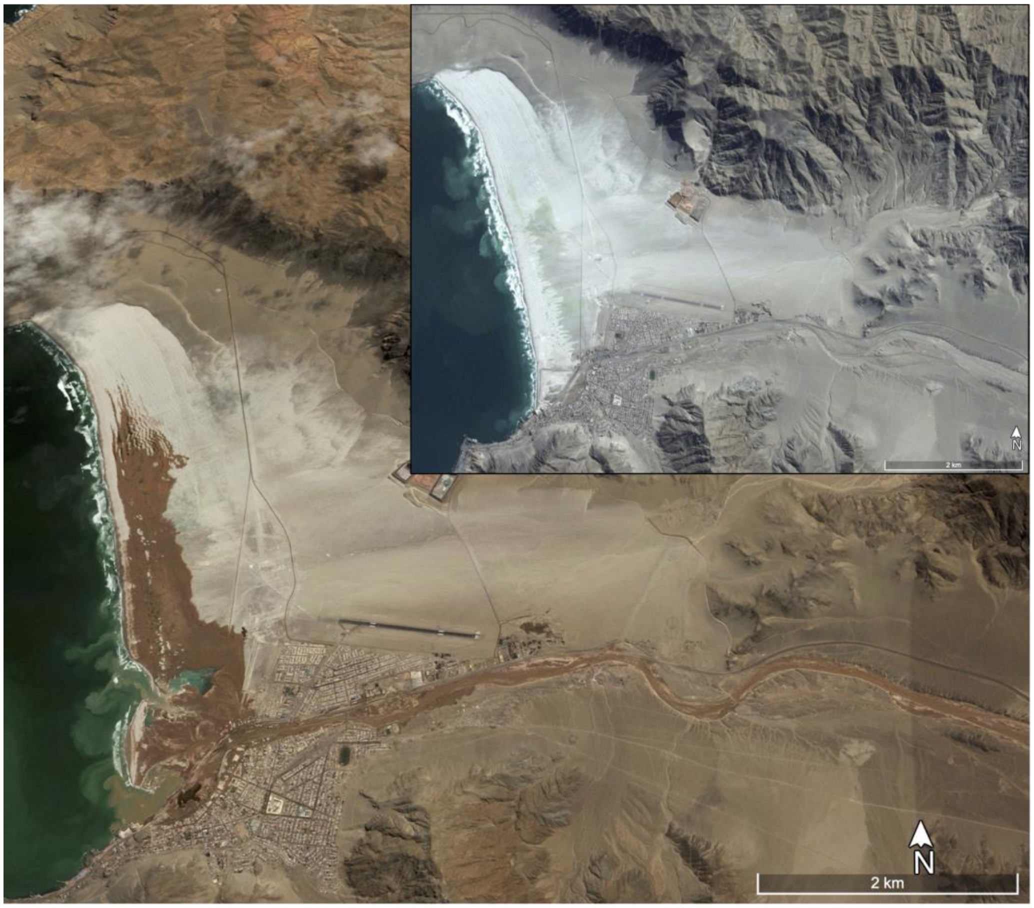

Figure 1 Google Earth images showing the Salado river, Chañaral and Chañaral beach before (23 July 2013, inset) and after (05 April 2015) the 24–26 March 2015 flood event

Marquesa valley

Two years after the March 2015 floods, northern Chile was again affected, with parts of the Coquimbo and Atacama regions heavily inundated on 11–13 May 2017. Many areas in the Elqui river basin in the Coquimbo Region received over 100 mm of rain (some in less than eight hours and equating to about the annual rainfall), with one such area, the Marquesa valley, receiving 140 mm in 12 hours (Falcón, 2017). The valley runs northeast from where it meets the Elqui river and contains a number of active, inactive and abandoned tailings deposits. During the rainfall event, river flood peak flow may have reached 140 m^3/s (capacity 60 m^3/s) and several of the abandoned and inactive deposits suffered partial failure (Falcón, 2017), which subsequently led to tailings being deposited downstream in the Marquesa and Elqui valleys (Alfaro & Garrido, 2017). Figure 2 shows that most of the failed sections were located opposite landform promontories, with failures occurring along steeply inclined to vertical surfaces (Figure 3).

Figure 2 Google Earth image from February 2017 showing the nine inactive and abandoned tailings studied along the Marquesa valley bottom, with approximate zones of tailings eroded in May 2017 shaded red

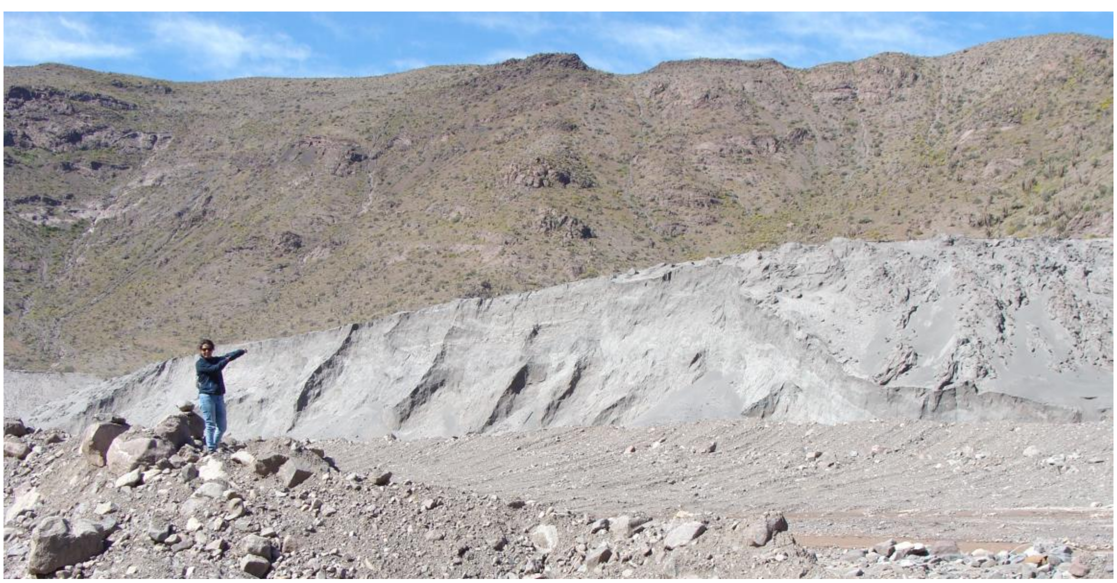

Figure 3 Eroded section of tailings deposit 3 (Figure 2) in the Marquesa valley photographed in September 2017 and showing the steep slope left after failure, which reveals internal stratification of tailings

METHODOLOGY

Chañaral beach

The volume of Chañaral beach tailings eroded during the 2015 flood event was estimated remotely using Google Earth, news reports and images, and ArcGIS. Figure 1 shows the beach before and soon after the event, from which the area of erosion was determined. The depth of eroded tailings was very difficult to estimate, as the flood not only eroded tailings, but also deposited a layer of brown sediment on top of them (Figure 1). From the few places where clear images exist, the depth of tailings eroded in the backshore was about 1.8 m; it is anticipated to have been less in the foreshore, but no clear images from this zone have been found.

Marquesa valley

In 2017, SERNAGEOMIN undertook a post-flood survey along the Marquesa valley and visually estimated that a total of 125 975 m^3 of tailings had been lost from the nine facilities under consideration in our study (Falcón, 2017). Using field photographs, Google Earth Pro and ArcGIS, a desk-based validation of this estimate was undertaken for the locations identified in Figure 2. Two methods were employed, both based on Spiekermann et al. (2017) for quantifying riverbank erosion.

The first method used images from Google Earth Pro prior to the flood event (February 2017) and field photographs taken soon after the event (June and September 2017) to estimate the width, height and slope angle of each of the missing parts of the deposits at three equidistant intervals along the length of the failure, which allowed calculations of the cross-sectional areas of eroded sections. By multiplying by the length of the failure, the eroded volume of each deposit was then estimated. When estimating slope angles from field photographs, it was necessary to assume that those of eroded sections had been the same as those of non-eroded sections.

At the time of employing the first method, Google Earth Pro imagery after the flood event did not exist. When this became available in October 2020, a second method was engaged that used polygon layers of the tops and bases of the tailings facilities before and after the flood event to enable changes in surface areas to be calculated in ArcMap. Tailings heights and slope angles were estimated using Google Earth Pro and cross checked with approximations from field photographs. These parameters then allowed estimation of tailings volume loss.

RESULTS AND DISCUSSION

Chañaral beach

The area of Chañaral tailings beach eroded was estimated to be 675 000 m^2 (Stile, 2020). If 1.8 m is taken as the maximum erosion depth, then the greatest volume of tailings eroded would have been

1 215 000 m^3. This figure is expected to be an overestimate, but suggests that at least several 100 000 m^3 of tailings were scoured from the beach and transported into the ocean.

Marquesa valley

The results of the two methods for estimating the Marquesa tailings losses are presented in Table 1 and compared to the estimates reported by Falcón (2017). Despite reasonable agreement in the totals, there is significant discrepancy between several of the individual estimates. Without access to the tailings sites, it is not possible to ascertain which results are most accurate. If the lowest and highest values are taken for each facility, the total loss lies between about 77 000 m^3 and 150 000 m^3. Overall, the results suggest something of the order of 100 000 m^3 of tailings were lost.

Table 1 Estimated volumes of tailings lost from facilities in Figure 2 during the May 2017 flood event in the Marquesa valley (all values are in cubic meters)

Tailings facility[a]	Authorized volume[a]	SERNAGEOMIN (Falcón, 2017)	Method 1 (Ryder, 2020)	Method 2 (Liu, 2021)
1 (Inactive)	274 332	30 000	36 000	27 000
2 (Inactive)	415 450	0	0	0
3 (Inactive)	162 210	40 000	42 000	9 300
4 & 5 (Inactive)	268 376	55 050	40 000	41 000
6 (Abandoned)	105 436	25	0	0
7 (Inactive)	271 500	50	0	5 000
8 (Inactive)	1 615 200	100	0	580
9 (Inactive)	111 800	750	900	11 000
Totals	3 224 304	125 975	118 900	93 880

[a] From Falcón (2017) and SERNAGEOMIN (2020). The authorized volume represents the maximum permitted volume of tailings and is indicative of the stored volumes in the facilities listed.

0 Indicates either not detected or not determined.

Limitations and uncertainties

All methods were hampered by the reliance on secondary data, the paucity of pre- and post-flood information, particularly for the vertical data on erosion and failure, and the resolution of the Google Earth imagery. The inability to ground truth parameters and to test estimates immediately after the flood events is likely to have created uncertainties, especially for estimating heights and slope angles of eroded and failed sections. Almost immediately after the flood events, processes occurred that removed evidence; for example, in the Marquesa valley, earth was moved and levees constructed to channel the river and to protect the bases of tailings deposits. Despite all limitations, the volumes calculated are presented as being indicative of the orders of magnitude of the volumes of tailings eroded.

Erosion mechanisms and magnitudes

The primary erosion mechanism at Chañaral beach was scour caused by the flood water flowing down the Salado river. Along the Marquesa section, it appears that flood water eroded and undercut the toes of tailings deposits, causing the material above to detach along steep to vertical brittle failure surfaces and fall or topple (Figure 3). Such brittle behaviour implies that the tailings acted as bodies of cemented sand and silt, which is consistent with the maturity of the deposits. These proposed mechanisms for the Marquesa section are hypotheses at this stage and could be tested through site investigation, additional image analysis and eye-witness accounts.

The severity of tailings failures may be quantified using various parameters, with one of them being the volume of tailings released. In their analysis of tailings failures from 1910 to 2010, Bowker and Chambers (2015) classified large-magnitude failures as either "Serious" or "Very Serious"; respectively, these correspond to the release of more than 100 000 m^3 and at least 1 000 000 m^3 of tailings. The incidents at Chañaral and along the Marquesa valley may not be typical tailings failures, but the volumes eroded are suggestive of a Serious to Very Serious event for the former and a Serious event for the latter. Thus, it is proposed that both cases represent volumetrically significant events (with the caveat that volume estimations could be validated by other means), but how do they rank in the context of failures in Chile?

Villavicencio et al. (2014) compiled data on 38 failures of sand tailings dams in Chile from 1915 to 2010, with 31 incidents attributed to earthquakes, six to heavy rainfall and one undefined. Failure flow volumes are reported unequivocally for 18 incidents, with two of them ranking as Very Serious (maximum 2 800 000 m^3) and both induced by earthquakes. Four correspond to Serious events, with only the 15 June 1915 failure of the Agua Dulce dam at Sewell in the O'Higgins Region caused by heavy rain and overtopping, which generated a tailings flow of 180 000 m^3. Consequently, the 2015 Chañaral and 2017 Marquesa events are likely to represent two of the most significant tailings volume releases in Chile. To the best of our knowledge, this is the first time that the magnitudes of these events have been formally recognized.

Such magnitudes demonstrate the need to evaluate the risk associated with flood-induced tailings erosion and failure in the center and north of Chile, where almost all Chile's inactive and abandoned tailings exist as unprotected and unvegetated piles or dumps inadequately isolated from the environment. Many of these are located in completely dry or ephemeral river and stream beds, or on their margins, and are therefore highly exposed to flash floods. By identifying tailings exposed to high probabilities of flood erosion and associated failure, action may be taken to reduce exposure, such as removing tailings or constructing protective barriers or water diversions. As a first step in this process of risk reduction, future exposure of tailings to flash floods under various climate change scenarios must be understood (e.g., Perez et al., 2021), noting that intensification of storms like those of 2015 and 2017 may increase this century in northern Chile (e.g., Ortega et al., 2019).

CONCLUSION

The extreme hydrometeorological events of 2015 and 2017 in northern Chile demonstrate that flood-induced tailings erosion and failure may lead to Serious to Very Serious tailings incidents in terms of volumes released. The 2015 Chañaral beach and 2017 Marquesa valley events should be recorded as two of the most significant tailings incidents in Chile and act as a catalyst for assessing the exposure of inactive and abandoned tailings to flash floods and the likelihood of their associated erosion and failure. Such assessment should be extended to other countries hosting tailings in arid and semi-arid climate zones.

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