Lessons Learned from Analysis of Los Frailes Tailing Dam Failure

M. Shahriari(✉) and M.E. Aydin

Konya Necmettin Erbakan University, Konya, Turkey
madi.shahriari@gmail.com

Abstract. Tailing dams are used to store mining tailings as uneconomic fraction of an ore after separating the valuable fraction. Tailing dams are mostly hazardous. Therefore, release of a large amount of tailings could lead to serious and long term ecological effects with very high cleanup costs. A literature survey shows that the main causes of tailing dam failure are poor design, improper site, irresponsibility and lack of control. To avoid of tailing dam failure awareness about the root causes and the severity of impacts on environment and human health is very important. This study is focused on a case to identify the causes as a base for proposing some important safety factors to prevent failure of tailing dams. The past experiences show that efforts should be put on prevention rather than reacting after the event.

Keywords: Mine tailing dam failure · Dam failure environmental impacts · Tailing dam design

1 Introduction

A tailings dam is typically an earth-fill embankment dam which is used to store mining tailings as uneconomic fraction of an ore after separating the valuable fraction [1]. Tailings could be solid, liquid, or slurry of fine particles. Solid wastes are often used as part of the tailing dam structure itself. Tailings of many mines such as lead and zinc, copper, gold and uranium, contain toxic substances, which pose big challenges for the long term containment.

Tailings dams rank among the largest engineered structures on earth. Among them The Syncrude Mildred Lake Tailings Dyke in Alberta, Canada, is the largest tailing dam structure on earth by volume with about 18 km long and from 40 to 88 m high [1].

It should be noted that tailing dams are designed for permanent containment. Therefore, design, and control during the construction and operation are very important tasks to avoid structural failure.

Tailing dams are often built with steep slopes using the solid fraction of the mining wastes/tailings thereby saving on cost [2]. In fact, preventing structural failure of tailing dams is an important task in mine waste management. Generally these tailing dams are vulnerable to failure due to poor design, constructing dyke by solid waste materials from the mining operation, lack of standards and regulations on design, specially in developing countries and high maintenance cost after mine closure [3].

P. Arezes (ed.), *Advances in Safety Management and Human Factors*,
Advances in Intelligent Systems and Computing 604, DOI 10.1007/978-3-319-60525-8_32

The world tailing dam failure rate over the last century is estimated as 1.2% for 18401 mine sites. This rate is much higher than the failure rate of the conventional water dam, which is reported to be as 0.01% [4].

In recent decades mining industry has experienced several tailing dams failure in association with very costly outcomes. Some of them are shown in Table 1.

Table 1. Some historical tailing dam failure [5]

Date	Location	Company	Mine type	Amount of release	Impacts
25 Apr. 1998	Los Frailes (Spain)	Boliden Ltd.	zinc, lead, copper, silver	4–5 million m^3 of toxic water and slurry	Thousands of hectares of farmland covered with toxic slurry
30 Jan. 2000	Baia Mare, Romania	Aurul S.A., Australia (50%), Remin S.A. (44.8%)	gold recovery from old tailings	100,000 m^3 of cyanide-contaminated liquid	Contamination of the Somes/ Szamos stream, tributary of the Tisza River, killing tonnes of fish and poisoning the drinking water of more than 2 million people in Hungary
4 Oct. 2010	Kolontár, Hungary	MAL Magyar Aluminium	Bauxite	700,000 m^3 of caustic red mud	Several towns flooded, 10 people killed, approx. 120 people injured, 8 km^2 flooded
4 Nov. 2012	Sotkamo, Kainuu province, Finland	Talvivaara Mining Company	nickel, (uranium by-product planned)	Hundreds of thousands of m^3 of contaminated waste water	Nickel and zinc concentrations in nearby Snow River exceeded the values that are harmful to organisms tenfold or even a hundredfold, uranium concentrations more than tenfold
7 Aug. 2014	Buenavista del Cobre mine, Cananea, Sonora, Mexico	Southern Copper Corp.	Copper	40,000 m^3 of copper sulphate	Flow into the 420 km-long Bacanuchi river, 800,000 people were directly affected

Shahid Azam and Qiren Li [2], have carried out a world wide analysis regarding tailing dam failure. Analysis has been done on 18401 mining sites over a time period covering last century called as pre-2000 (1910–1999) and post-2000 (2000–2009) events. They could identify 198 pre-2000 failure events and 20 post-2000 failure events. Number of tailing dam failures in the period of 1910–2009 are shown in Fig. 1.

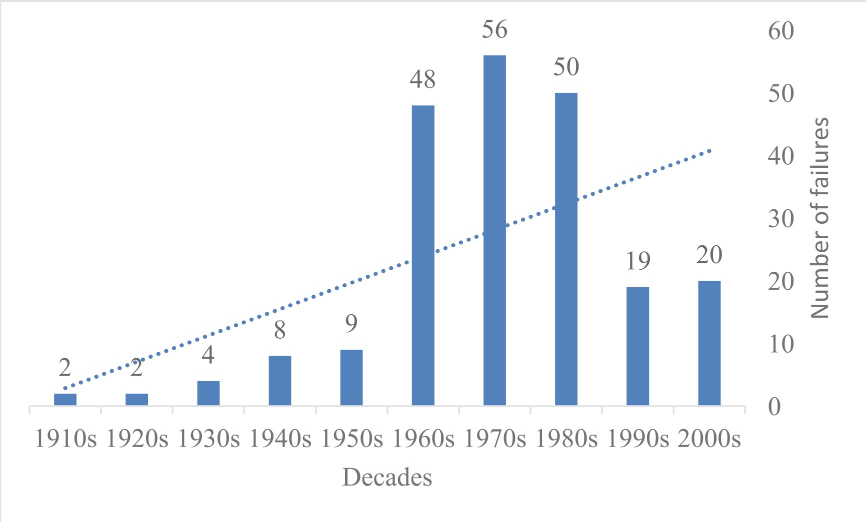

Fig. 1. Tailing dam failure over the time. Adapted from [2]

As far as the regional failures are concerned, of 198 pre-2000 cases most of the accidents have been occurred in North America (36%), Europe (26%) and South America (19%) respectively. Looking at the 20 post-2000 cases of the sites under the study, Europe and Asia are blamed for 60% of the failure events in this period. Table 2 shows regional failure case distribution in the of the study carried out by Azam and Li [2].

Table 2. Regional tailing dam failure (1910–2009). Adapted from [2].

Regions	North America	South America	Europe	Asia	Africa	Australia
Number of studied mine sites	8652	1825	1168	1584	1624	3548
Failure cases (pre-2000)	72	38	52	17	12	7
Failure cases (post 2000)	5	2	6	6	1	0

As it is shown in Table 2, failure cases have increased in Europe and Asia during post-2000.

According to the literature, the main causes of tailing dam failure could be overtopping, weather (climate changes), poor management, and poor design and construction [2].

The main impacts of tailing dam failure are environmental damage, health problem, human losses and capital losses such as infrastructure, agriculture farms and dam itself.

Tailing dam events which have been associated with significant impacts on environment, human health and life and capital in some parts of the world could be considered as a warning for improving safety criteria in tailing dam design and operation. It should be noted that a large number of tailing dam incidents remain unreported specially in developing countries. This could be a serious hinder for development of safety standards and regulations in this field.

This study is focused on failure cause analysis through applying Swiss Cheese Model which has been developed by Reason [6]. The Model will be applied to identify the root causes of failure of Los Fraile tailing dam, which occurred in Spain 1998. The goal of the study is to find the basic criteria, which are needed to design a safer tailing dam.

2 Case Description

On April 25, 1998, the Los Frailes lead-zinc mine experienced a foundation failure due to sliding surfaces in the ground, leading to the dam breaking and releasing between 4 and 5 million cubic meters of mine tailings. The mine tailing, being acidic and containing several heavy metals, poured into the nearby river Rio Agrio. The river rose 3 m, flooding thousands of hectares of farmland. This has later been called the Doñana incident. Rio Agrio is a tributary to Rio Guadimar, which flows through Doñana National Park. The water eventually finds its way into the Mediterranean. It was therefore crucial to gather and handle the waste as soon as possible. However, the cleanup operation took a total of three years and had an estimated cost of €240 million [7].

The Los Frailes mine is owned by a Spanish subsidiary of the Swedish/Canadian company Boliden. Boliden has, though not presenting a report of their own, stated that the accident was caused by force majeure, and could therefore not be predicted and Boliden could not be blamed. However, this statement has been criticized. In fact, the problem with sliding surfaces in the ground was identified two years earlier [7] (See Fig. 2).

The bottom of the dam consisted of marl. The chemicals contained in the dam reacted with the calcium carbonate in the marl, causing it to decompose. Thus, the mechanical stability of the soil was deteriorating. Boliden had recently been applying for a licence for doubling the dam's capacity. Therefore, one can raise hypotheses that the dam was deliberately overloaded. Boliden has refused to pay any compensation for damages, still referring to the accident as a result of force majeure.

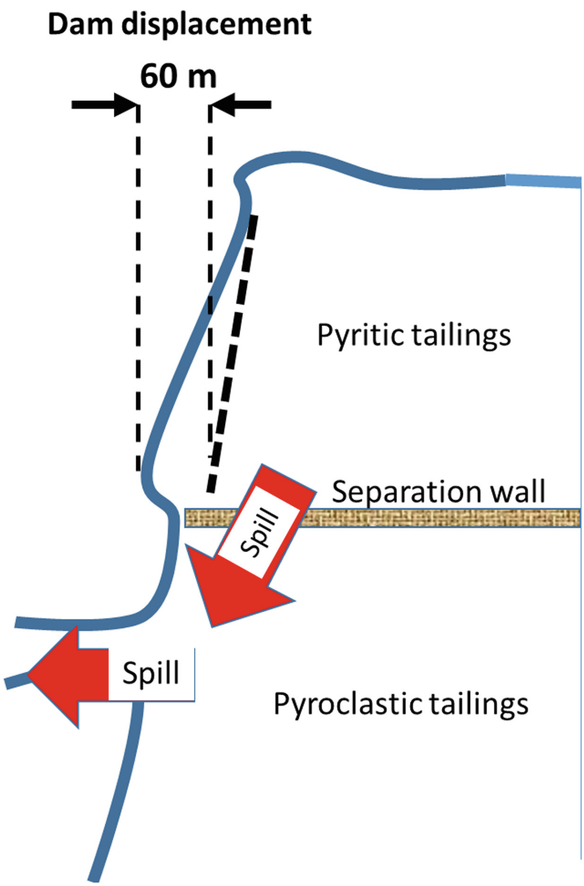

Fig. 2. Spill due to sliding surfaces in the ground

3 Swiss Cheese Model Description

The Swiss Cheese Model as shown in Fig. 3, is developed by James Reason to analyze causes that lead to an accident. According to Reason, each slice of cheese represents a barrier or defense layer that prevent the hazard from passing through, leading to an accident subsequently [8]. Example of barriers includes adopting a properly designed safety system, proper procedures of maintenance and provides adequate training to the workers. However, these barriers might not be functioning perfectly. There might be weaknesses present in these defense layers and each of the weaknesses represents a hole on the slice of cheese [9]. The weaknesses of the defense layer might be arisen from latent condition or active failure [6]. Both failures have the potential to trigger an accident. Latent failure is inevitable within the system and it normally exists due to the decisions made by the top management who sets the goal [9]. There are two major effects of the presence of latent failure in the system. It either creates a working environment which is prone to error-making condition or a permanent hole on the defense layer that weaken the whole system [6]. Latent failures remain dormant in the system for a long period of time before they combined with active failure to trigger an accident [6]. This may be introduced at the time a tailing dam was designed or may be associated with management decisions and policies. Active failure is due to the unsafe act committed by people who are working on the decision or those who are working in front of the system [6]. The unsafe act can be further classified as intended or unintended actions. Intended actions can be categorized as mistake or violation whereas unintended action includes slip and lapse [6]. The position of the holes on the defense layers is continuously changing [6, 8]. These holes are located at different positions on each defense layers. Hence, even if there are holes on the defense layer, accident might not occur because hazards might not be able to penetrate the subsequent defense layer due to different positions of the holes (see Fig. 3). Conversely, when the holes on all the defense layers are aligned into a straight line, there is a potential that hazards could penetrate through the layers and trigger an accident (see Fig. 3).

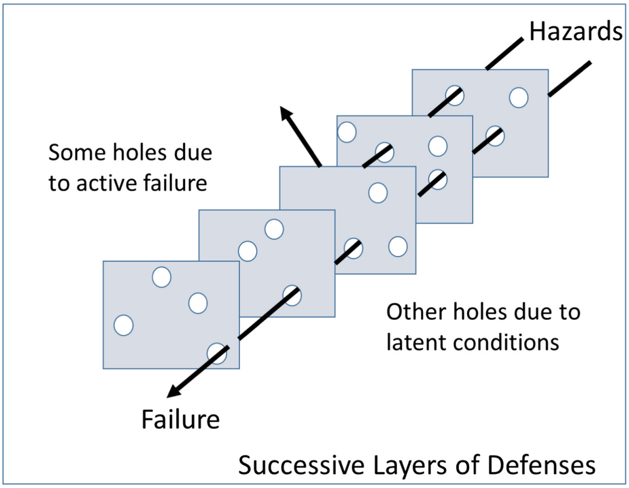

Fig. 3. Swiss Cheese Model with either non-aligned holes on the defense layers or aligned holes on the defense layers (Adapted from [10])

It should be noted that most accidents (or system failure) can be linked to one or more of five levels of failures: organizational influences, unsafe supervision, preconditions for unsafe acts, the unsafe acts themselves and in adequate defenses.

4 Analysis of the Accident

The failure of Los Frailes tailing dam has been analyzed using the Swiss cheese model (see Fig. 4). For the analysis of the case, 5 safety barriers were recognized as shown in Fig. 4.

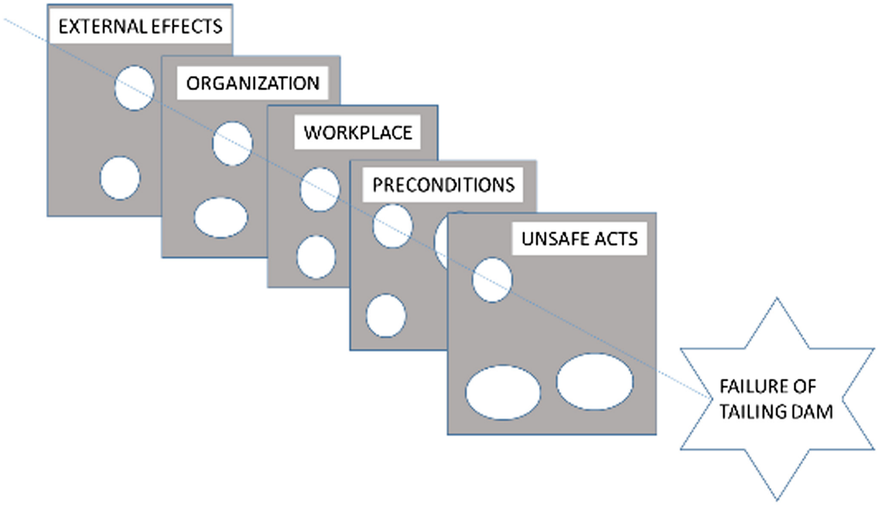

Fig. 4. Safety barriers recognized in Los Frailes Tailing Dam

The analysis of the case is summarized in Table 3.

Table 3. Results of the analysis of the case under the study

Category	Description
External effects	● No serious enforcement/didn't follow the directives ● Poor control
Organization	● Poor design ● Improper site selection ● No care about the reports of two consultancy firms like Geocisa and Golder Associates AB, which found the weak points two years before the failure ● No coordination between two projects for building the tailings dam ● No safety culture ● Neglecting the regulations
Workplace	● No management change policy ● No monitoring and control: Lack of instruments for working correctly due to absence of working inclinometers ● Neglecting the regulations ● No risk assessment and emergency planning and responses ● Poor maintenance and no reporting system
Preconditions	● Type of material in the soil (marl) ● Dam built at the top of expansive clays ● Water presence where dry conditions were expected ● High pressure of water in the clayey foundation ● No communication ● Lack of knowledge ● Vibration due to the blasting at the nearby mine
Unsafe acts	● Overloading the dam ● Lack of foresight ● Late reaction after awaking of water presence where dry beaches should be expected and even when they found failure with electric cable due dam structure movement ● Problems of the deformations not accounted at all ● No care about not working instruments

5 Results and Conclusion

Analysis of the case under the study shows that lack of safety culture, poor design in terms of ignorance of interfere of soil and tailing material, improper site, irresponsibility, lack of control, no monitoring and reporting have been the main causes for the failure. These problems are mostly due to weaknesses in the protection layers of organization and management. In other word Boliden company has failed to create a security base to prevent the dam failure. On the other hand, the company has worldwide mining activities experiences. Therefore, it was expected to manage the crisis. This accident and the similar event, which occurs about one per year [4], could cause very harmful environmental crises. Therefore, more attention should be payed, in design, site selection, monitoring, control, and finally effective crises management to minimize the serious impacts on the environment. The results from the Los Frailes tailing dam failure were used to give general recommendations for integration of safety into the life cycle of tailing dams. These includes:

- *Design and Site Selection:*
  - site assessment (geology, seismicity, climate, upstream catchment area,…) and selection
  - hazard scenarios identification considering heavy rain, flood, blasting, earthquake etc.
  - analysis of anticipated dam failure impact (travelling path of slurries, downstream land use and water use,…)
  - selection of embankment type
  - assessing interferes of soil and the tailing material
- *Construction:*
  - Using right technology and materials
- *Observation and control:*
  - regular monitoring of dam movements,…
- ***Improve stability of existing tailings impoundments*** by for instance construction of diversion dams to prevent flood inflow, smoothing of slopes, etc.
- ***Considering long-term safety and failure modes other than complete embankment failure*** (such as seepage, dust, long-term erosion, bio-intrusion, etc.)

While embankment breaks are the most spectacular failure mode for tailings dams, the long-term hazards should not be neglected either. This requires efficient measures to contain these hazards in the long term.

References

1. Tailing dam, from Wikipedia, the free encyclopedia.https://en.wikipedia.org/wiki/Tailings_dam
2. Azam, S., Li, Q.: Tailings dam failures: a review of the last one hundred years (2010). http://www.infomine.com/library/publications/docs/Azam2010.pdf
3. Rico, M., Benito, G., Salgueiro, A.R., Diezherrero, A., Pereira, H.G.: Reported Tailings Dam Failures: A Review of the European Incidents in the Worldwide Context. Elsevier, Amsterdam (2007)

4. ICOLD: Tailings dams - risk of dangerous occurrences, lessons learnt from practical experiences. Bulletin 121 (2001)
5. Chronology of major tailings dam failures. http://www.wise-uranium.org/mdaf.html
6. Reason, J.: Human error: models and management. BMJ **320**, 768–770 (2000). doi:10.1136/bmj.320.7237.768
7. The Los Frailes tailings dam failure (Aznalcóllar, Spain), 27 February 2015. http://www.wise-uranium.org/mdaflf.html
8. Perneger, T.V.: The Swiss Cheese Model of safety incidents: are there holes in the metaphor? BMC Health Serv. Res. **5**(71) (2005). Published online. doi:10.1186/1472-6963-5-71. http://www.ncbi.nlm.nih.gov/pubmed/16280077
9. Swuste, P.: Qualitative methods for occupational risk prevention strategies in safety or control banding—safety. Saf. Sci. Monit. **11**, 1–7 (2007)
10. Department of Community and Family Medicine: Swiss Cheese Model, Duke University Medical Center (2005). Retrieved from http://patientsafetyed.duhs.duke.edu/module_e/swiss_cheese.html