Tailings Dam Failures: A Review of the Last One Hundred Years

Shahid Azam
Qiren Li

Introduction

Tailings dams are some of the largest earth structures geotechnical engineers construct. These embankments are often built with steep slopes using the coarse fraction of the tailings thereby saving on cost. To keep such impoundments standing is one of the most challenging tasks in mine waste management. Generally, these containment facilities are vulnerable to failure because of the following reasons: (i) dyke construction with residual materials from the mining operations; (ii) sequential dam raise along with an increase in effluents; (iii) lack of regulations on design criteria, especially in developing countries; and (iv) high maintenance cost after mine closure (Rico et al., 2007). For a world inventory of 18401 mine sites, the failure rate over the last one hundred years is estimated to be 1.2%. This is more than two orders of magnitude higher than the failure rate of conventional water retention dams that is reported to be 0.01% (ICOLD, 2001).

The mining industry has experienced several significant dam failures in recent history: Merriespruit (South Africa), 1994; Omai (Guyana), 1994; Los Frailes (Spain), 1998; Baia Mare (Romania), 2000; and Aitik (Sweden), 2000. An acute societal concern over such events has resulted in enforcing stringent safety criteria at mining operations in some parts of the globe. However, the standard of public reporting varies considerably from country to country and from region to region. A large number of tailings dam failure incidents remain unreported or lack basic information when reported. This has seriously hindered the development of safety regulations in such areas. Despite insufficient data, a generalized statistical analysis is exigently needed to help minimize tailings dam failure events.

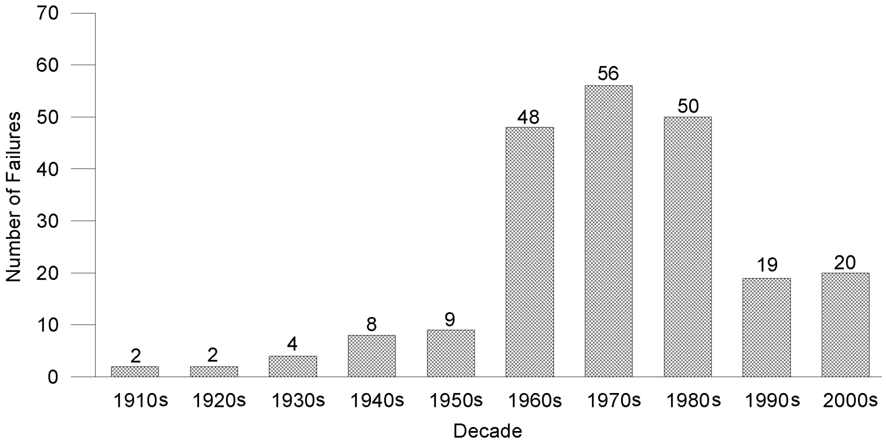

Figure 1. Failure events over time.

Scope of this Study

A comprehensive worldwide database for all historical failure events is virtually inexistent. Still, a number of databases can be used in conjunction. The primary databases are given as follows: (i) United Nations Environmental Protection (UNEP); (ii) International Commission On Large Dams (ICOLD); (iii) World Information Service of Energy (WISE); (iv) United States Commission On Large Dams (USCOLD); and (v) United States Environmental Protection Agency (USEPA). Even these databases should be considered as subsets of the actual number of tailings dam failure incidents in the world. Nonetheless, this article attempts to statistically analyze the available data on tailings dam failures by dividing the failure events into two time groups, namely: pre-2000 events and post-2000 events.

A total of 198 pre-2000 events and 20 post-2000 events were identified. Among the former, 147 and all of the post-2000 events contained enough information to help conduct the analyses. A significant portion of the reported failures had to be categorized as "un-

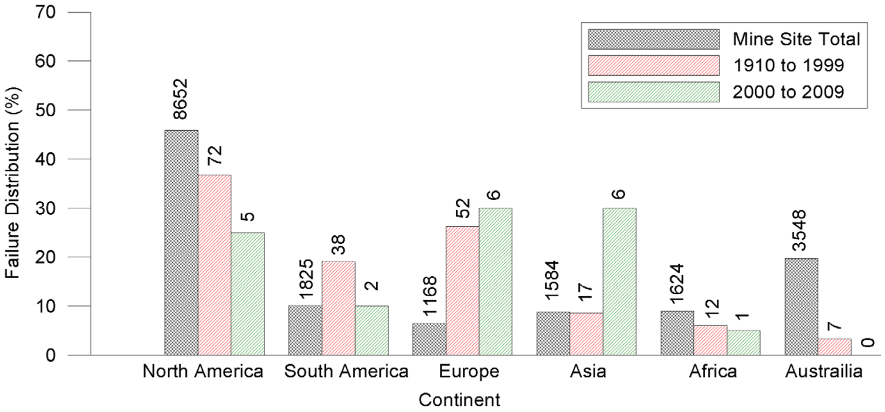

Figure 2. Failure distribution by region.

known" because of missing data on a certain parameter. The analyses focused on understanding tailings dam failures with respect to time and space, causes, and consequences. To compare data within the two time groups, failure distributions for various parameters were calculated using the following formula:

Failure Distribution (%) = (Cases in a parameter/Cases in a time group) × 100

Temporal and Spatial Distributions

Figure 1 summarizes failure events over time. Tailings dam failures remained around 8 to 9 per decade in the 1940s and 1950s but peaked to around 50 events/decade during the 1960s, 1970s and 1980s. The high failure rate during these later decades may be attributed to an increased mining activity immediately after World War II to address the high global demand for metals, minerals, and raw materials. This demand was related to post-war reconstruction in North America and Europe and to the initial development of newly independent countries at the end of colonialism in Asia and Africa. With sufficient engineering experience, implementation of tougher safety criteria, and improved construction technology, failures were significantly reduced in the 1990s and remained at about 20 events/decade in the 1990s and 2000s.

Figure 2 gives the regional failure distribution in relation to mine site totals. Of the 198 pre-2000 cases, most failures occurred in North America (36%), Europe (26%), and South America (19%). Conversely, the 20 post-2000 cases primarily took place in Europe and Asia with a combined failure distribution of 60%. Despite the high mining activity in North America, South America, Africa, and Australia, the decline in failure events in these regions over the past decade is attributed to an improved engineering practice. Meanwhile, the Asian and European mining operations have experienced an increased failure rate because of a booming Chinese economy requiring vast metal and mineral resources and a higher reporting from Eastern Europe after the demise of communism. Clearly, tailings dam failure incidents have shifted geographically from developed countries to developing countries. Therefore, it is crucial for these countries to learn from the post-war experience of the developed countries to reduce tailings dam failures.

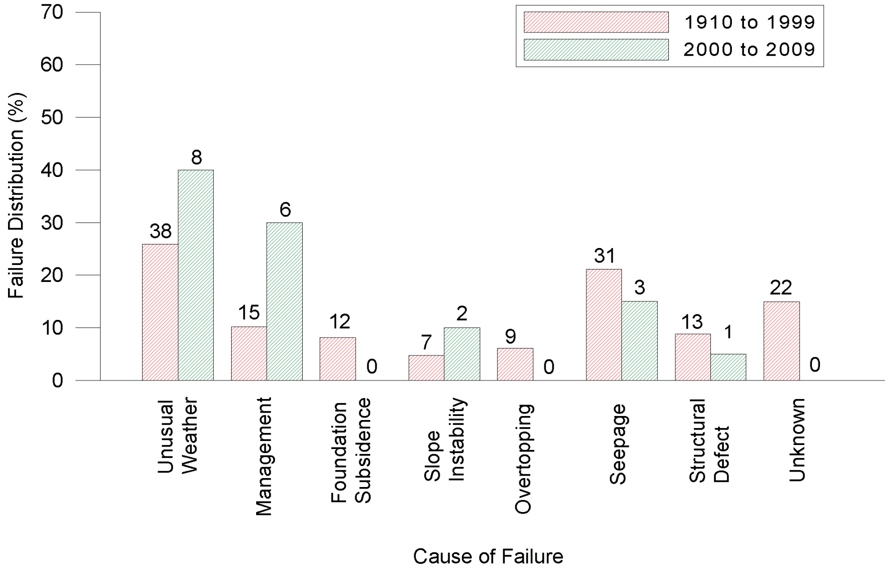

Figure 3. Failure distribution by cause.

Causes of Failure

Figure 3 illustrates the distribution of tailings dam failures by cause. This figure differentiates the climatic and managerial reasons of dam failure from the mechanicisms of failure. Failures due to unusual rain increased from 25% pre-2000 to 40% post-2000. This might be attributed to the recent changes in climatic conditions, particularly at mine sites close to the seas and/or located in equatorial regions that have received high precipitations. As such conditions may increase in both numbers and severity, dam design in such areas must incorporate the effect of climate change. Likewise, failures due to poor management accounted for 10% and 30%, respectively, for the two time groups. This increase indicates the rush for natural resource exploitation while compromising on engineering standards in various parts of the globe. According to Rico et al. (2007), poor management includes inappropriate dam construction procedures, improper maintenance of drainage structures, and inadequate long-term monitoring programs. The climatic and managerial reasons have a bearing on all of the mechanisms of tailings dam failure.

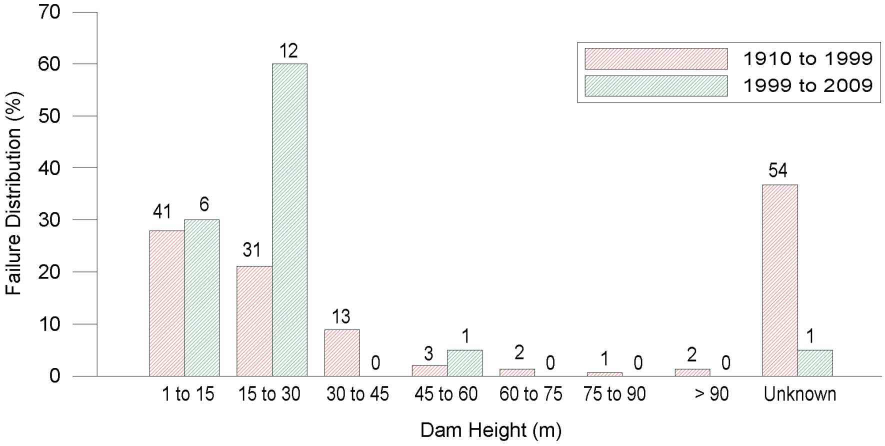

Figure 4. Failure distribution by dam height.

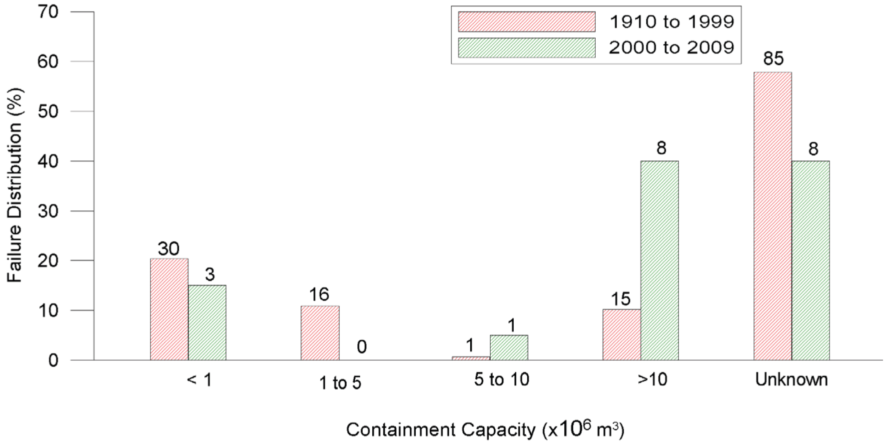

Figure 5. Failure distribution by containment capacity.

Geotechnical engineers have long understood the importance of observing pore water pressures and embankment deformations in tailings containment facilities. This is because these data correlate well with several types of failure and as such provide a basis to rectify the situation throughout the mine life and beyond (Peck, 1969). We must learn to earn the confidence of multi-disciplinary teams, which are operative at mine sites, to ensure the safety of tailings dams. Perhaps, we have learnt that message with regards to seismic liquefaction (that results in swift and drastic events), where failures of this type have dropped from 14% in pre-2000 cases to zero in post-2000 cases:the 2010 Chilean earthquake of magnitude 8.8 did not cause any failure. Good earthquake designs are partly because of our understanding of dynamic loading such as blasting that is common practice at mine sites.

Figure 4 shows the distribution of tailings dam failures by dam height. Failures are found to mainly occur in dams with heights of up to 30 m. A plausible reason may be that unconsolidated materials with high pore water pressures in such relatively low dams (possibly in their early stages of development) are yet to develop adequate shear strength to counter the resisting forces. This is especially the case when the tailings dams are constructed using the upstream method that is still a common practice in some of the developing countries (Vick, 1999). Further, a comparison of the two time groups reveals that failure in dams of up to 15 m height increased from 28% to 30% whereas failure in dams with heights between 15 m to 30 m increased from 21% to 60%. The recent increase in failure of such dam heights may be attributed to the combined effect of rapid dyke construction along with poor monitoring. This is particularly true for some of the re-opened mines (due to increased commodity prices in the 2000s) for which the tailings containment facilities were raised based on pre-closure construction practice.

Figure 5 gives the distribution of tailings dam failures by containment capacity. This figure corroborates well with data in the previous figure by indicating that about 31% (pre-2000 events) of failures occur in small to intermediate size facilities that contain up to 5 x 10^6 m^3 of tailings. The drop in such events to 15% in the post-2000 cases may be ascribed to containment geometry requiring low dams. Similarly, the increase in tailings dam failures from 10% to 40% in large dams (storing in excess of 10 x 10^6 m^3 of tailings) should be due to one or more of the afore-mentioned reasons.

Impact of Failures

Figure 6 summarizes the failure distribution by tailings release amount. The figure illustrates that a significant portion (29% for pre-2000 cases and 40% for post-2000 cases) of the dam failures released up to 0.5 x 10^6 m^3 of tailings to the environment. This correlates well with data depicted in Figures 4 and 5 where a comparable number of incidents fell in small to intermediate size dams. The current figure shows that usually about one-fifth of the contained volume is released. Even such volumes are sufficient to cause extensive damage to life, property, and health. For example, 0.5 x 10^6 m^3 of released tailings are enough to drown about 1200 North American style single-family homes.

Figure 7 illustrates the distribution of tailings dam failure by socio-economic impact. Failures were assigned to a certain parameter that best described the actual incident. The main impacts were found to be environmental pollution, loss of life, and infrastructure damage. Parameters such as environmental pollution and infrastructure damage were found to respectively decrease from 52% and 20% for pre-2000 events to 35% and 15% for post-2000 cases. This is in accordance with the above findings that about one-

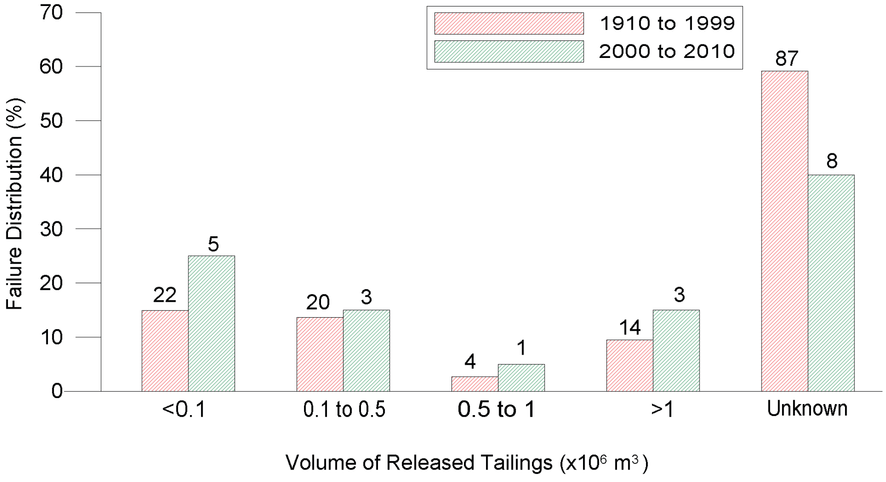

Figure 6. Contaminant release during failure.

third of the failures occur in small to intermediate size facilities: the released tailings from such failures can be managed relatively easily because of their smaller amounts. The relative increase in impact on public health and loss of life should be associated with the failure of large dams.

Summary and Conclusions

This article aimed at understanding the tailings failure history using a statistical approach. Whereas a significant portion of failure incidents fell under the "unknown" category, some general trends were developed with respect to time and space, causes, and consequences. The main findings of this work can be summarized as follows:

1. Tailings dam failures peaked to around 50 events/decade in 1960s through 1980s but have dropped down to about 20 events/decade over the last twenty years. The frequency of such incidents has recently shifted geographically from developed countries to developing countries.
2. The main reasons for dam failures are "unusual rain" and "poor management" and these causes have a profound effect on failure mechanisms. The inclusion of climate change effects in the initial design and of the observational method during construction, maintenance, and monitoring are highly desirable.
3. Failures predominantly occur in "small to medium" size dams that are up to 30 m high and contain a maximum tailings volume of 5 x 10^6 m^3. Such incidents can be minimized by employing proper engineering standards and by avoiding upstream construction as much as possible.
4. Upon dam breakage, the released tailings generally amount to about one-fifth of those contained within the facilities. Environmental pollution and infrastructure damage can be managed in "intermediate failures". Loss of life and health issues are associated with large catastrophic spills.

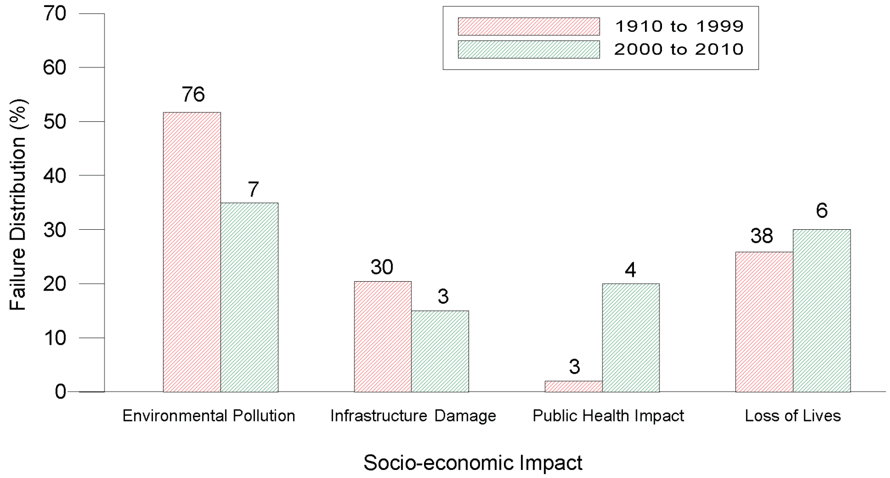

Figure 7. Socio-economic impact of failure.

References

ICOLD (2001). *Tailings Dams - Risk of Dangerous Occurrences, Lessons Learnt from Practical Experiences*, Bulletin 121.

Peck RB. (1969). Advantages and limitations of the observational method in applied soil mechanics. *Geotechnique*, 19(1):171-187.

Rico M, Benito G, Salgueiro AR, Diezherrero A, and Pereira HG. (2007). *Reported Tailings Dam Failures: A Review of the European Incidents in the Worldwide Context*. Elsevier, Netherlands.

Vick SG. (1990). *Planning, Design, and Analysis of Tailings Dams*. BiTech Publishers Limited, Canada.

Epilogue

The recent dam failure in Hungary (October 4, 2010) that released about 700,000 m^3 of tailings and has a huge impact on life, property, health, and the environment, is a grim reminder of the importance of understanding these incidents more closely.

Shahid Azam, Ph.D., P.Eng.
Associate Professor
Environmental Systems Engineering,
University of Regina
Regina, SK, Canada, S4S 0A2
Tel: 1-306-337-2369
Fax: 1-306-585-4855
email: Shahid.Azam@URegina.CA

Qiren Li, B.A.Sc., EIT
Environmental Engineer
Clifton Associates Ltd.
Regina, SK, Canada, S4N 5Y5
Tel: 1-306-721-7611
Fax: 1-306-721-8128
email: qiren_li@clifton.ca