

The Role of Water Management in Tailings Dam Incidents

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ABSTRACT

This paper presents a review of tailings dam incidents, and examines the role water management on the causes and consequences of these incidents. The incident review includes data compiled by the US Society on Dams, International Commission on Large Dams, the United Nations Environmental Programme, and other available sources. The incident data (from 1900 through 2014) was evaluated and classified for dam characteristics, operating conditions, incident cause, and incident effects.

The number and type of incidents (ranging from a minor release with subsequent repair and reuse to a dam breach and tailings release), are shown as functions of history, dam height, and incident cause. The results demonstrate that both ponded and interstitial water are contributing factors in the causes and consequences of these incidents.

Elimination of future tailings dam incidents would be aided by managing ponded water in the tailings impoundment so that the probabilities for overtopping the dam, seepage and piping, and dam slope instability are reduced. In addition, transition of the tailings from a saturated deposit with a resulting high potential for flow to an unsaturated deposit with no potential for flow would reduce the likelihood of downstream consequences from a tailings dam incident.

Key Words: Tailings impoundment; Mine waste management; Dam failures

1 INTRODUCTION

This paper presents a review of documented tailings dam incidents, with the intent of drawing from this information to identify best practices or lessons learned for future operations. The effect of water and water management on the causes and consequences of these incidents is included in the review.

1.1 Water Storage Dam Data

The International Commission on Large Dams (ICOLD) and its US counterpart, the US Society on Dams (formerly the US Committee on Large Dams or USCOLD) have actively documented design issues and performance of water storage dams. ICOLD created the World Register of Dams in 1958, has maintained and updated this register (ICOLD, 2011a). ICOLD has continued to publish guidelines on dam design, construction, and monitoring, in order to disseminate information on dam safety (ICOLD, 1987, 2013).

ICOLD first approved a proposal in 1964 to study known failures and incidents arising from rock foundations and accidents to large dams. USCOLD published two reviews of water storage-dam incidents (USCOLD, 1976, 1988). From the updated review published in 1988, over 500 water-storage dam incidents were tabulated. These documents also outlined the terms for classification of incidents (ranging from failures with complete abandonment of the dam to varying levels of accidents with repairs to the dam or outlet works). Incident causes were grouped into categories (overtopping, slope stability, earthquake, foundation, seepage, structural, erosion, or subsidence). The results from USCOLD (1988) are summarized graphically in Figure 1. This graph shows that major failures were due to overtopping and erosion, and major repairs were associated with spillway and outlet works.

WATER STORAGE DAM INCIDENT AND CAUSE

■ FAILURE WITH ABANDONMENT OF DAM
■ FAILURE WITH SUCCESSFUL REPAIR OF DAM
■ ACCIDENT DURING DAM CONSTRUCTION OR INITIAL FILLING
■ ACCIDENT DURING DAM OPERATION
■ MAJOR REPAIRS

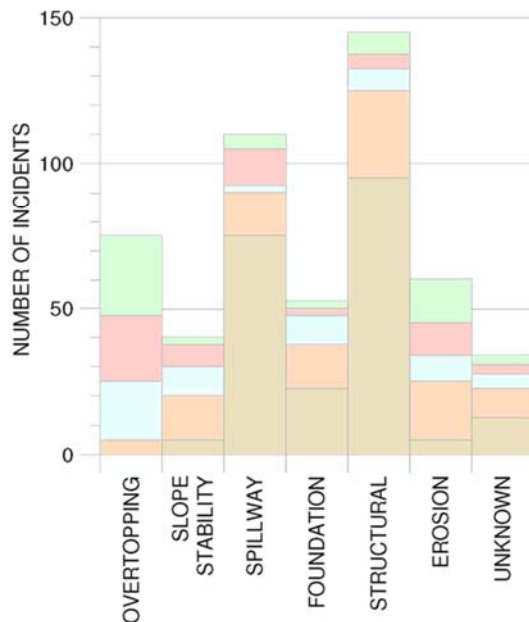


Figure 1. Incident summary for water storage dams.

The U.S. Bureau of Reclamation has maintained a record of dam incidents in their inventory. From the incidents and number of dams in operation, a failure frequency was estimated (von Thun, 1985). For earthfill and rockfill dams in the U.S. constructed after 1960 and within a dam height range of 50 to 300 feet (15 to 91 m), the estimated annual failure frequency is 6.2×10^{-4} .

1.2 Tailings Dam Data

The Tailings Dam Committee of ICOLD has published compilations of tailings dams (ICOLD, 1989) and guidelines on tailings dam analysis and design (including ICOLD, 1982, 2011b). A more specific reference on tailings dam analysis and design is Vick (1990).

The USCOLD Tailings Dam Committee (under the chairmanship of Steve Vick) conducted a survey of tailings dam incidents in 1989, with the results published by USCOLD in 1994 (USCOLD, 1994). The results of this survey were presented in a format similar to the USCOLD water storage dam review. The USCOLD review identified 185 worldwide tailings dam incidents from 1917 through 1989, from publications, questionnaires, and anecdotal information. Impounding structures not related to mill tailings (such as coal refuse structures, ash dams, or industrial waste lagoons) were not included in the review.

In 1996, the United Nations Environmental Programme (UNEP) published a survey of tailings dam incidents conducted by Mining Journal Research Services (UNEP, 1996). This survey included the incidents in USCOLD (1994), as well as incidents that occurred after 1989. UNEP (1996) identified 26 incidents that were independent of the 185 incidents identified in USCOLD (1994).

In 2001, the ICOLD Committee on Tailings Dams and Waste Lagoons published a tailings dam incident survey incorporating the incident data base from USCOLD and UNEP (ICOLD, 2001), resulting in a data base of 221 incidents with varying level of detail. This data base was summarized in Strachan (2002). There are other tailings dam incident reviews that are

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independent of the USCOLD and ICOLD reviews discussed above. These include Szymanski (1999), Davies et al. (2000), Martin and Davies (2000), Cambridge (2001), Davies (2002), Martin et al. (2002), Rico et al. (2007), and Azam and Li (2010). The updated survey of tailings dam incidents discussed in this paper is based on the data sources outlined below.

1.3 Update of Tailings Dam Incident Data

The updated review of tailings dam incident data expands the total number of independent incidents to 288. The level of detail for each incident varies from knowledge of a failure at a location and date (and nothing else) to detailed knowledge of a failure after cleanup, investigation, determination of cause, and litigation.

Table 1. Summary of Incident Data Sources.

Source of Data	Number of Incidents	Percent of Incident Total
USCOLD, 1994	185	64
UNEP, 1996	26	9
ICOLD, 2001	10	3
Lottermoser, 2007	26	9
Caldwell, 2014	4	1
Villavicencio, 2014	15	5
WISE, 2015	22	8

1.4 Incident Terms

In this review, the term “tailings dam” is used, and refers to the embankment or confining portion of tailings impoundments, tailings storage facilities, tailings management areas, or tailings disposal facilities. Tailings are limited to mill process tailings (or tailing). Coal refuse or ash disposal facilities, heap leach facilities, and waste rock storage facilities were not included in the incident review.

The definitions used in this review are consistent with the definitions used in previous USCOLD publications. The term “incident” is used to be consistent with these publications, and includes failures (indicating breach of the dam and loss of process water or tailings), accidents (indicating repairs made to the dam with no loss of process water or tailings), and groundwater issues (indicating seepage or groundwater impact issues that were inconsistent with design intent).

Unknown incidents comprise events that were known at a location and date, but with no additional information. When additional information is available, data on dam type, dam fill type, dam height, active/inactive status, incident type, and the cause of the incident are included. The incident data varies, and includes in many cases some, but not all of this information.

2 DISCUSSION OF REVIEW RESULTS

The results from the updated incident review are discussed in the following sections. The results are of use for general information, with the limitations in the data understood. The documented tailings dam incidents in the data set comprise a subset of the total number of incidents that have occurred. The reported incidents in recent years comprise nearly all actual incidents, due to low likelihood of unreported incidents. The percentage of reported incidents in the early 20th century is likely to be low, due to a high likelihood of unreported incidents. Detail in types of dams and other distinguishing information is highly variable. Incident causes are shown based on the cause reported in the source of information. Actual causes may be due to a series of events, which are not reflected in the documented results.

2.1 Incident History

Figure 2 shows the incident history, in terms of number of incidents in five-year increments from 1900 to 2015. The increase in the number of incidents in the 1960s corresponds with construction of larger-capacity mills and availability of large earthmoving equipment for dam construction. Similar charts showing incident history have been presented in Azam and Li (2010) and other publications. Martin et al. (2002) present the incident history in comparison with water storage dam incidents (from data in ICOLD, 1995). A similar trend is shown with water-storage dams, corresponding with dam construction with large earthmoving equipment in the 1960s.

Figure 2 also shows that most of the recorded incidents are dam failures.

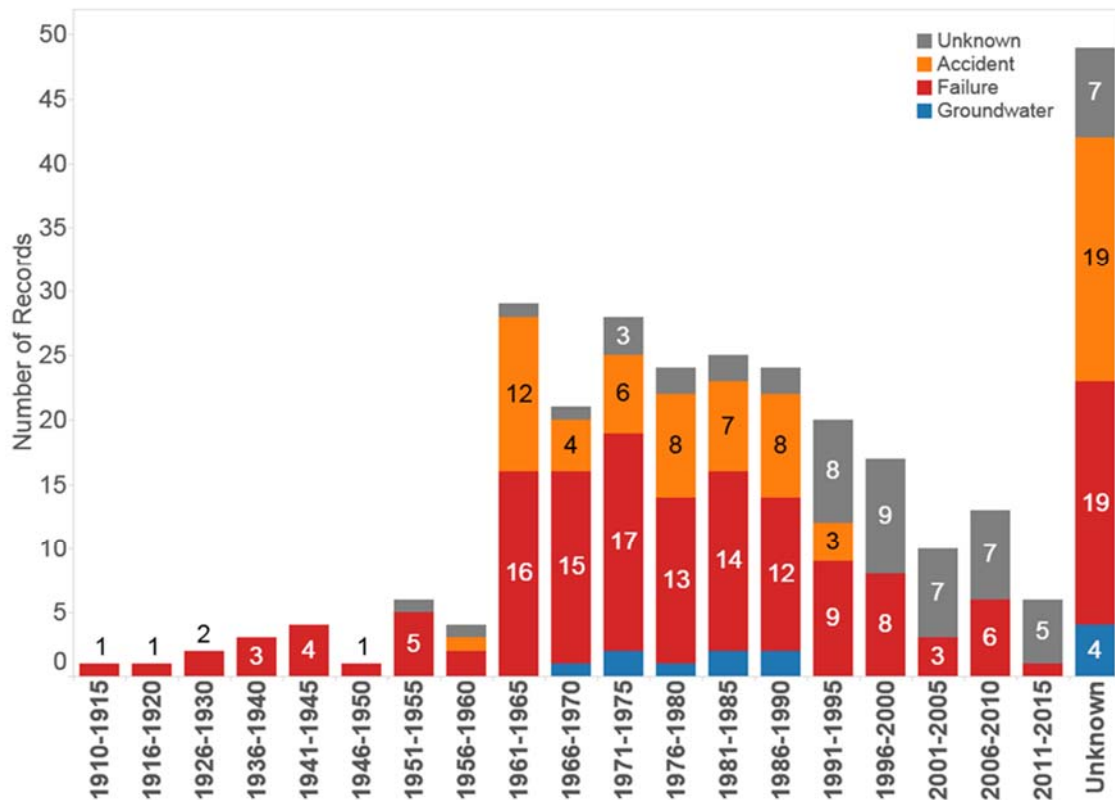


Figure 2. Incident review history and incident type.

2.2 Incident Location

Figure 3 summarizes the incidents by country. The incidents are on continents and in countries where there has been significant mining activity. The relatively large number of incidents in the U.S. reflects the number of facilities in early operation and more thorough incident reporting.

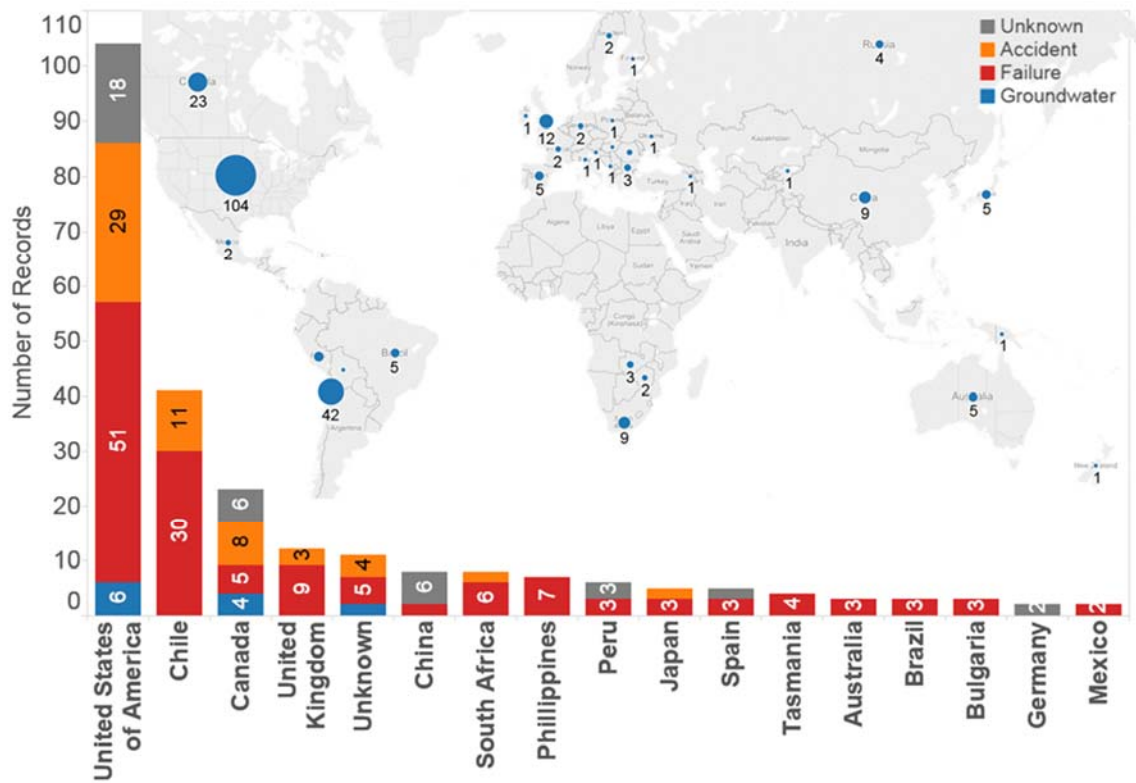


Figure 3. Incident type and location.

2.3 Dam Height

Figure 4 shows incidents with dam height in 5-foot (1.5-m) increments. The larger number of incidents with dam heights of less than 50 feet (15 m) is most likely due to two factors: (1) the larger number of tailings dams constructed at lower heights, and (2) the larger number of tailings dams constructed earlier in the 20th century that were not designed, constructed, and monitored to current standards of practice.

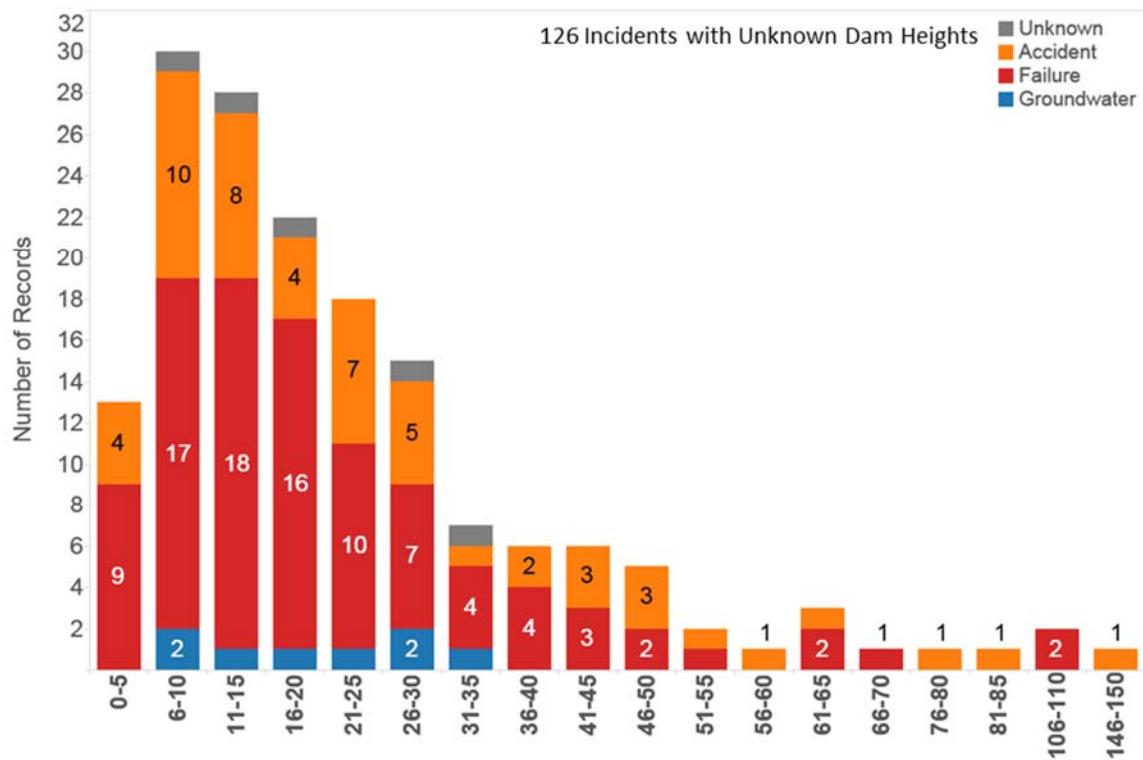


Figure 4. Dam height and incident type.

Figure 5 shows incidents with dam height in terms of whether the dam was in operation or inactive at the time of the incident.

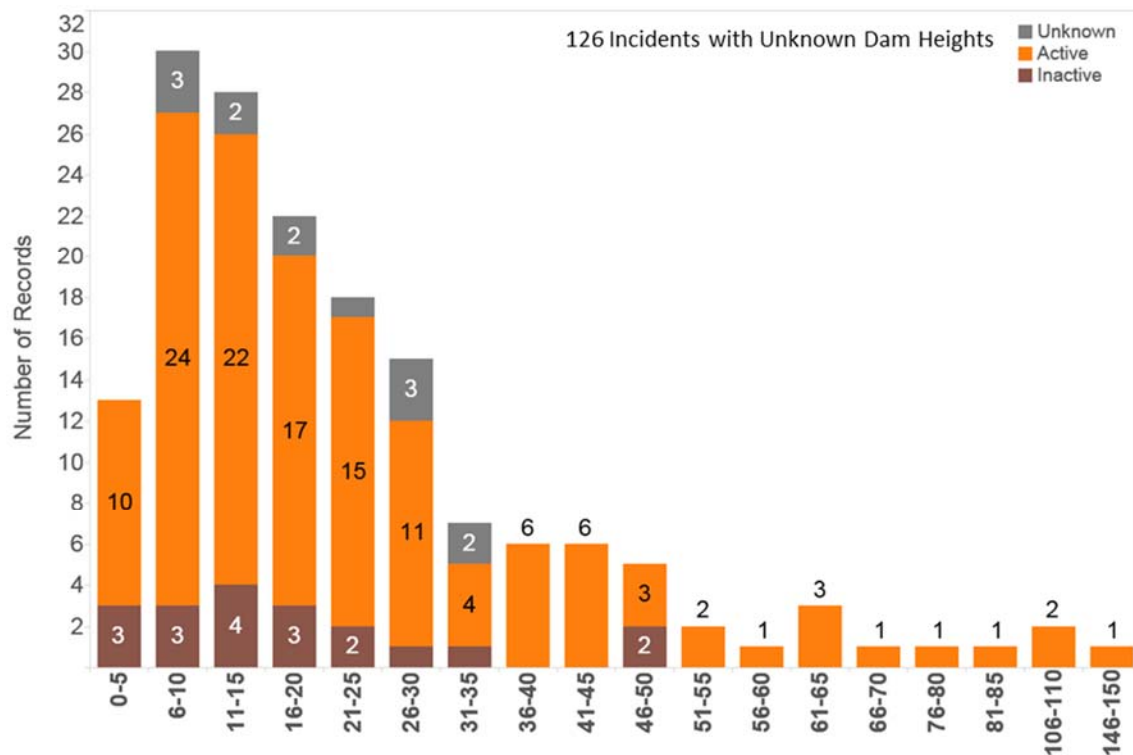


Figure 5. Dam height and active/inactive facility.

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2.4 Incident Causes

The reported cause of incident is shown in Figure 6 with respect to the incident type. The incident causes are consistent with the causes reported in USCOLD (1988 and 1994), and are summarized below.

- Slope instability – movement of the dam slope
- Earthquake – effects from a seismic event
- Overtopping – water overtopping the dam crest
- Foundation – seepage or piping of solid materials in the dam foundation
- Seepage – seepage or piping of solids materials within the dam
- Structural – deficiencies in the spillway, decant system, or tailings delivery system
- Erosion – erosion damage on the dam slopes
- Mine subsidence – subsidence resulting in process water or tailings flow into underground workings

Incidents with an unknown cause are also included in the figure.

For the failures shown in Figure 6, slope instability, earthquake, and overtopping are the leading reported causes.

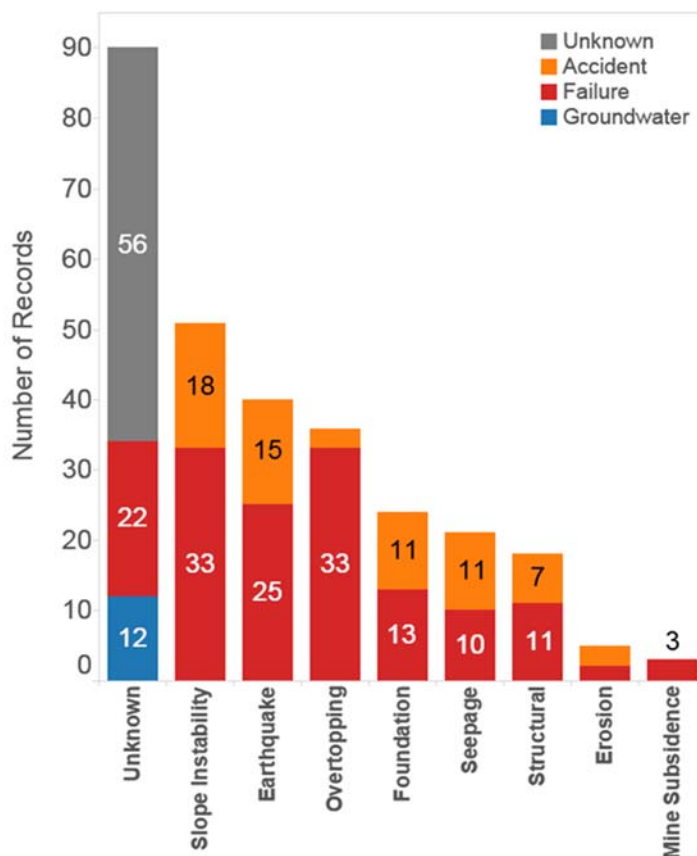


Figure 6. Incident cause and incident type.

The incident cause information is shown in terms of active or inactive facilities in Figure 7. The figure shows that the majority of incidents were associated with dams in active operation.

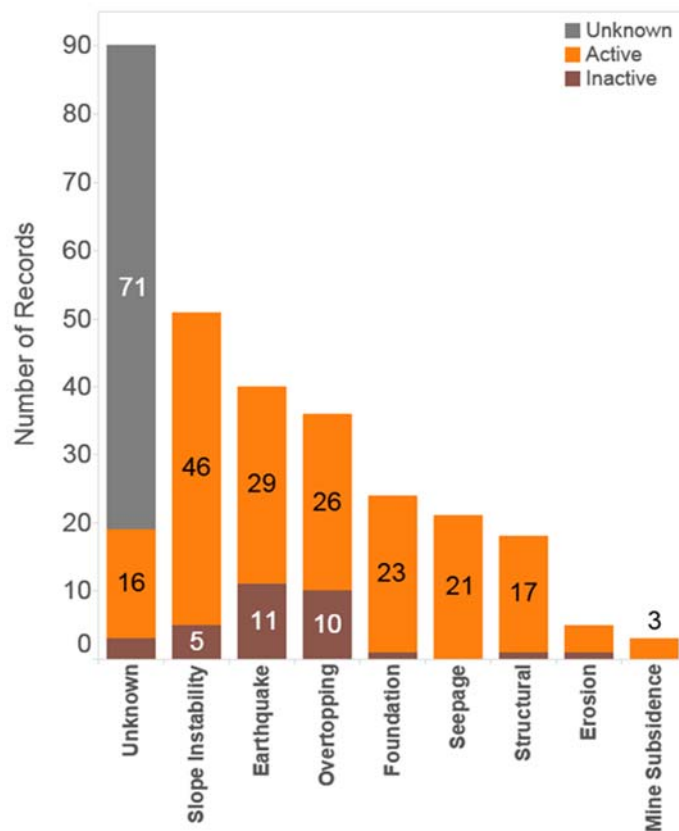


Figure 7. Incident cause and active/inactive facility.

The incident cause information is shown in terms of dam type in Figure 8. Where reported, tailings dam types are separated into four categories: upstream, downstream, centerline, and water retention. These types are summarized below.

Water retention dams refer to dams designed like a typical water-retention structure with a clay core or other hydraulic barrier, and constructed in one or more stages.

Upstream dams refer to the embankment being constructed in stages, with the embankment crest at each stage located upstream relative to the embankment crest of the previous stage (defined in Vick, 1990 and other references). Upstream dams were the first tailings dams that were constructed, with the embankment material comprised of tailings. Because of subsequent embankment raises being over previously deposited tailings, the shear strength and drainage characteristics of the underlying tailings are critical to the stability of the embankment.

Downstream dams refer to an embankment constructed in stages, with the embankment crest at each stage located downstream of the previous stage. The type of construction results in subsequent embankment raises being over previously constructed fill material or natural ground, and not tailings.

Centerline dams refer to an embankment constructed in stages, with the embankment crest at each stage located directly above of the previous stage. The type of construction results in subsequent embankment raises being over previously constructed fill, natural ground, or tailings.

The results of incidents with dam type in Figure 8 show that, although no type of dam is immune from incidents, the majority of incidents are associated with upstream-constructed dams. This is partially due to the large number of upstream-constructed dams that have been in operation, and the fact that many of these dams were constructed in the early 20th century in by trial-and-error methods. Many of the dams in the unknown column in Figure 8 are likely to be upstream-constructed dams.

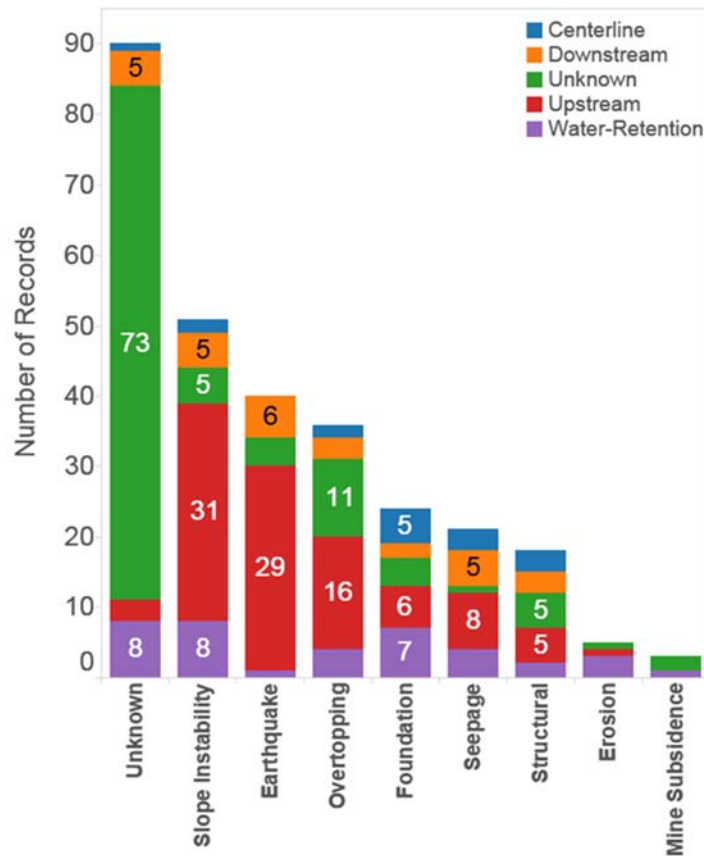


Figure 8. Incident cause and dam type.

3 CONCLUSIONS

From the data summarized in Figures 6, 7, and 8, most of the incidents are associated with the water management aspects of the dam, with incidents due to either water overtopping the dam or water seeping through the dam affecting slope stability or propagating erosion.

3.1 Water Management

The water management aspects are consistent with recommendations from the Mount Polley Independent Review Panel Report (IEEIRP, 2015) and summarized in Wilson and Robertson (2015):

... implementation of best available tailings technology, ... based on the principles outlined as follows:

1. *Eliminate surface water from the impoundment.*
2. *Promote unsaturated conditions in the tailings with drainage provisions.*
3. *Achieve dilatant conditions throughout the tailings deposit by compaction.*

These principles can be achieved with slurried tailings impoundments utilizing dams constructed by upstream, centerline, or downstream methods; co-disposal with waste rock; as well as impoundments utilizing thickened, paste, or filtered tailings processing. The key factors are proper design, construction, operation, and monitoring to manage surface water and tailings porewater.

As discussed in Wilson and Robertson (2015), elimination of surface water and promotion of unsaturated conditions is not consistent with environmental management strategies for chemical stability of sulfide-bearing tailings by maintaining saturated conditions. However, the potential From *Tailings and Mine Waste 2015*, Proceedings of the Tailings and Mine Waste 2015 Conference, University of British Columbia, October 26-29, 2015, Vancouver, B.C.

for a tailings dam incident with a release takes precedence over maintaining a water cover and saturated tailings conditions in a tailings dam.

3.2 Failure Frequencies

In comparison with water storage dams, earthfill and rockfill embankments comprise approximately 73% of the dams in operation, and approximately 75% of recorded incidents were associated with earthfill and rockfill embankments (USCOLD, 1976, 1988). As mentioned in Section 1.1, estimates by the U.S. Bureau of Reclamation indicated an annual water-storage dam failure frequency of 6.2×10^{-4} (von Thun, 1985). Estimates for water storage dams in Martin and Davies (2000) indicated an annual failure (not incident) frequency of 1×10^{-4} .

For tailings dams, Martin and Davies (2000) estimated that there are approximately 3,500 tailings dams in operation worldwide. From this number, estimates of annual failure frequency were 1×10^{-3} , and estimates of annual incident frequency were 1×10^{-2} (Martin and Davies, 2000). Tailings dam failure frequency in British Columbia was estimated in Appendix I of IEEIRP (2015). For 1969 through 2015, there have been roughly 110 to 120 tailings dams in operation. With seven failures over this period, the annual failure frequency is approximately 1.7×10^{-3} .

The higher annual failure frequency of tailings dams compared to water storage dams can be explained with the differences in construction and operation, where water storage dams are constructed in one stage, filled, and operated. If there are issues with the dam, water can be released to facilitate maintenance and repairs. Tailings dams are constructed in multiple stages and gradually filled with tailings. If there are issues with the dam, ponded water may be removed, but the tailings remain in place. However, the higher annual frequency of failure (or any failure) with tailings dams is not acceptable (as discussed in Vick, 1999; Martin et al., 2002), from corporate liability and cost, environmental, regulatory, or public relations standpoints.

3.3 Recommendations

Methods to reduce the frequency of incidents and failures include the following:

- Managing tailings facilities to minimize ponded water on the impoundment surface, and maintaining tailings beaches to keep ponded water away from the upstream slopes of tailings dams.
- Operating tailings facilities to optimize tailings densities by consolidation and drainage or by mechanical methods (such as thickening or filtration).
- Educating personnel involved with tailings facility operation and management to recognize proper tailings dam performance and best management practices, and know established procedures and actions to take when unforeseen conditions are observed.
- In evaluating new tailings facilities, considering alternative tailings management methods and their associated costs through the entire mine life cycle (including closure and post-closure periods).

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