CONCLUSIONS FROM EVALUATION OF TAILINGS DAM INCIDENTS

Clint Strachan, PE[1],
Breanna Van[2]

ABSTRACT

This paper summarizes a review of tailings dam incidents, and examines the key constituents contributing to the causes and consequences of these incidents. Comparisons are drawn with water-storage dams, and conclusions are presented on reducing the potential for future incidents.

The tailings dam incident review includes data compiled from available on-line sources and previous incident publications (including the US Society on Dams, International Commission on Large Dams, and the United Nations Environmental Programme). The incident data (from 1900 through 2016) was evaluated and classified for dam characteristics, dam height, and operating conditions.

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

Managing ponded water and saturated conditions in the tailings are key factors, so that the probability for overtopping the dam, occurrence of seepage and piping, and unacceptable dam slope stability are reduced. The likelihood of downstream consequences would also be reduced by transition of the tailings from a saturated deposit with low shear strength and a resulting high potential for downstream flow to an unsaturated deposit with sufficient shear strength to minimize potential for flow.

INTRODUCTION

This paper summarizes an updated review of documented incidents associated with tailings dams (also referred to as tailings impoundments or tailings storage facilities). Incidents discussed in this paper range from dam failures with release of tailings and water, to occurrences requiring dam repair but without release of tailings or water. The intent of this review is to compile lessons learned from these incidents and identify best practices for future operations. The effect of water and water management on the causes and consequences of these incidents is included in this review.

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[1] Principal Geotechnical Engineer, Stantec, 3325 South Timberline Road Suite 150, Fort Collins CO US 80525-2903, clinton.strachan@stantec.com
[2] Geologist, Stantec, 3325 South Timberline Road Suite 150, Fort Collins CO US 80525-2903, breanna.van@stantec.com

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 water-storage 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 (from Strachan and Goodwin, 2015).

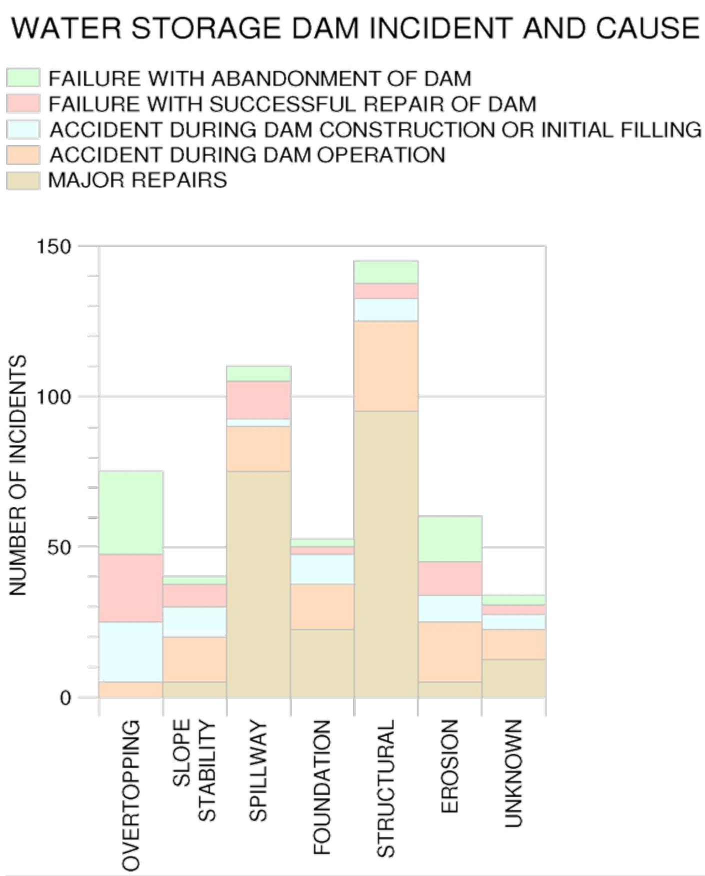

Figure 1. Incident summary for water storage dams.

Figure 1 shows that the majority of incidents were classified as major failures (not routine maintenance). The majority of incident causes were associated with structural features or outlet works and spillways. The causes of major failures were primarily overtopping and erosion.

The U.S. Bureau of Reclamation has maintained a record of dam incidents in their inventory, and from these incidents and number of dams in operation, estimated a failure frequency. 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 $6.2x10^{-4}$ (von Thun, 1985). Martin and Davies (2000) estimated an annual failure frequency for all water-storage dams of $1x10^{-4}$.

Tailings Dam Data

The Tailings Dam Committee of ICOLD has published a compilation of tailings dam documents (ICOLD, 1989) and guidelines on tailings dam analysis and design (including ICOLD, 1982, 2011b). A well-known book summarizing tailings characteristics and introducing 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 in 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. In order to focus on mill tailings incidents, 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). Other tailings dam incident reviews (that are independent of the USCOLD and ICOLD reviews) 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).

Update of Tailings Dam Incident Data

An updated review of tailings dam incident data through 2014 (Strachan and Goodwin, 2015) resulted in 288 independent incidents. This review included incidents related to coal refuse facilities. The additional review summarized in this paper resulted in 331 independent incidents. The level of detail for each incident varied 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.

Incident Terms

In this paper, 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) or coal processing residues. Coal ash impoundments, heap leach facilities, and waste rock storage facilities were not included in the incident review.

The term "incident" is used to be consistent with previous USCOLD 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 incident cause are included.

DISCUSSION OF REVIEW RESULTS

The 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 of the actual incidents, due to low likelihood of unreported incidents. Conversely, the percentage of reported incidents in the early 20th century is likely to be low, due to a high likelihood of unreported incidents. The level of detail in types of dams, operational factors, and other distinguishing information is highly variable.

Incident information of specific interest for lessons learned is the incident cause. Where information is available, incident causes are based on the cause reported in the source of information. For some tailings dam failures, the cause is in dispute. Furthermore, actual causes may be due to a series of events, such as a slope failure creating overtopping followed by dam breach. These series of events are not reflected in the results.

Considering the variability in incident information, the results from the updated incident review are discussed in the following sections.

Incident History

Figure 2 shows the incident history, in terms of number of incidents in five-year increments from 1900 to 2017. 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.

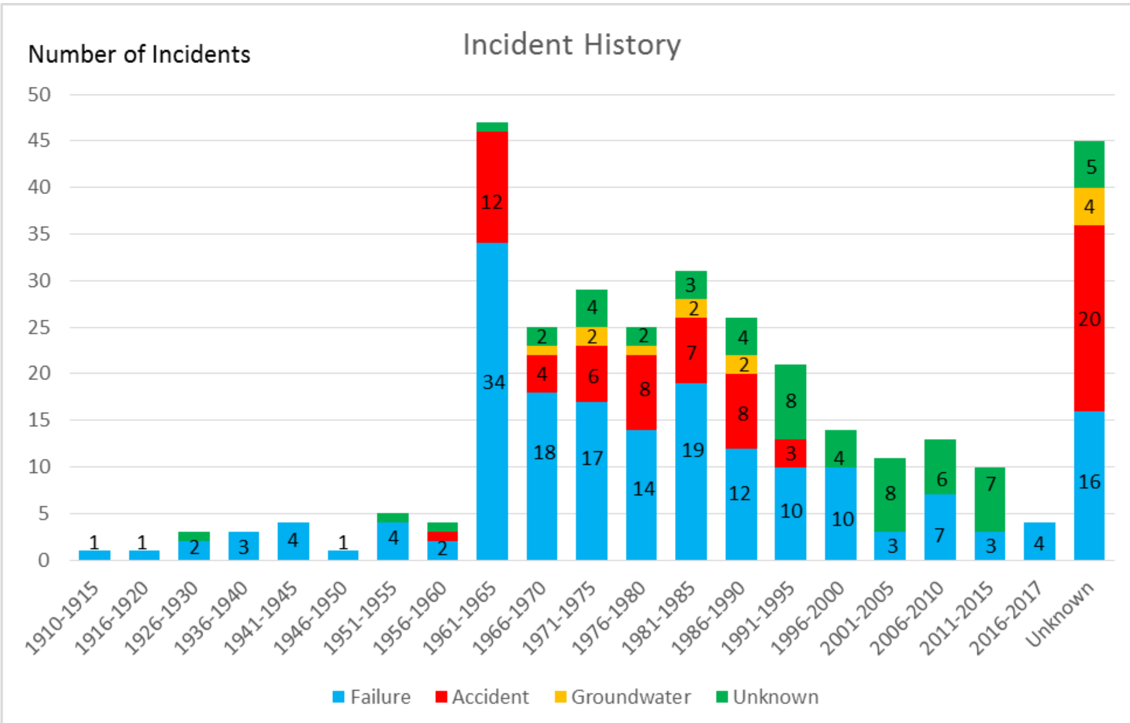

Figure 2. Incident review history and incident type.

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 most likely more thorough incident reporting.

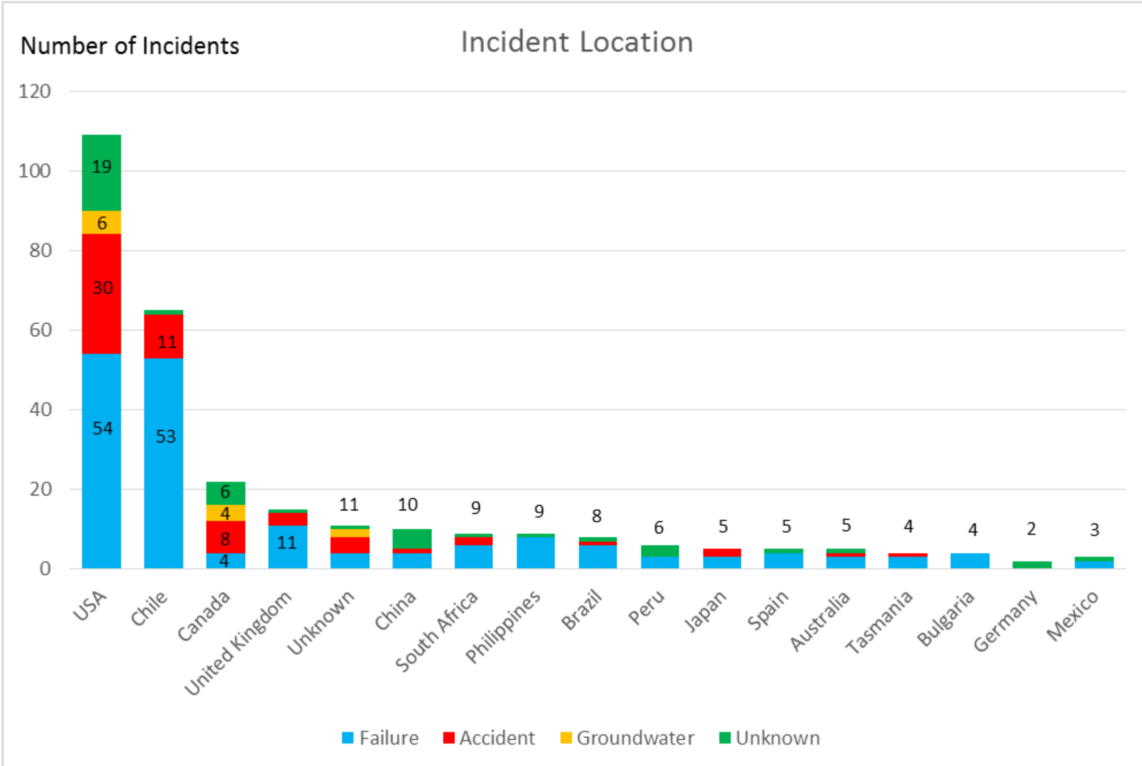

Figure 3. Incident type and location.

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.

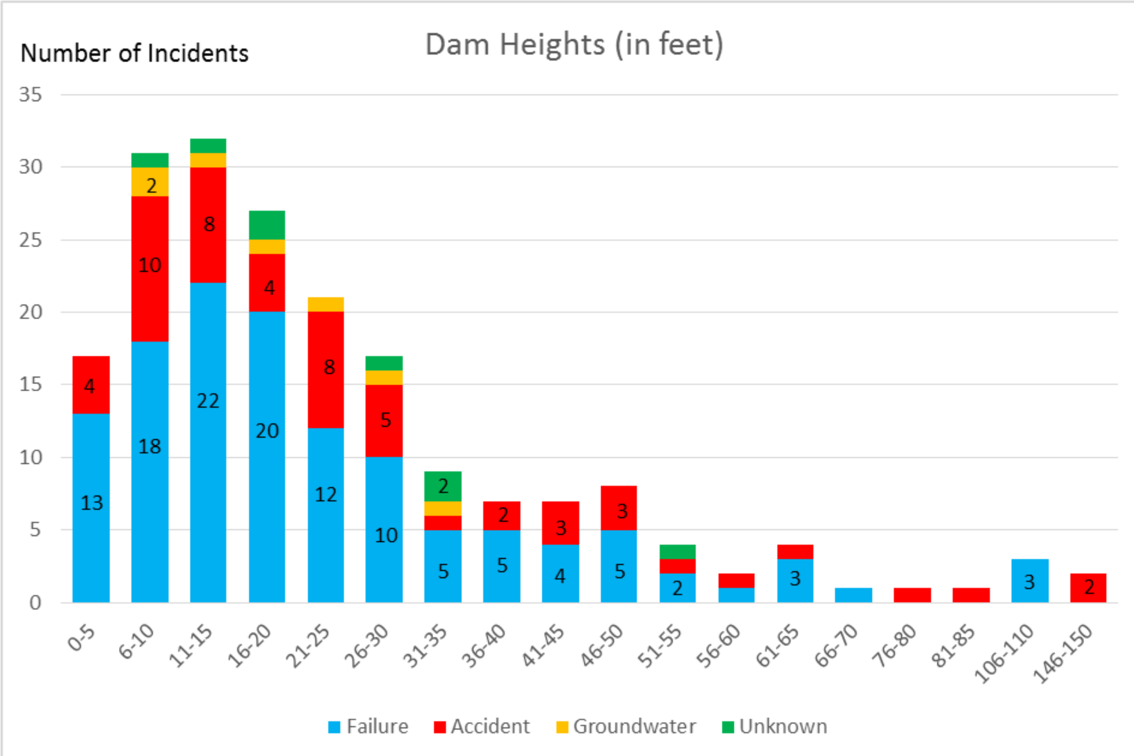

Figure 4. Dam height and incident type.

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

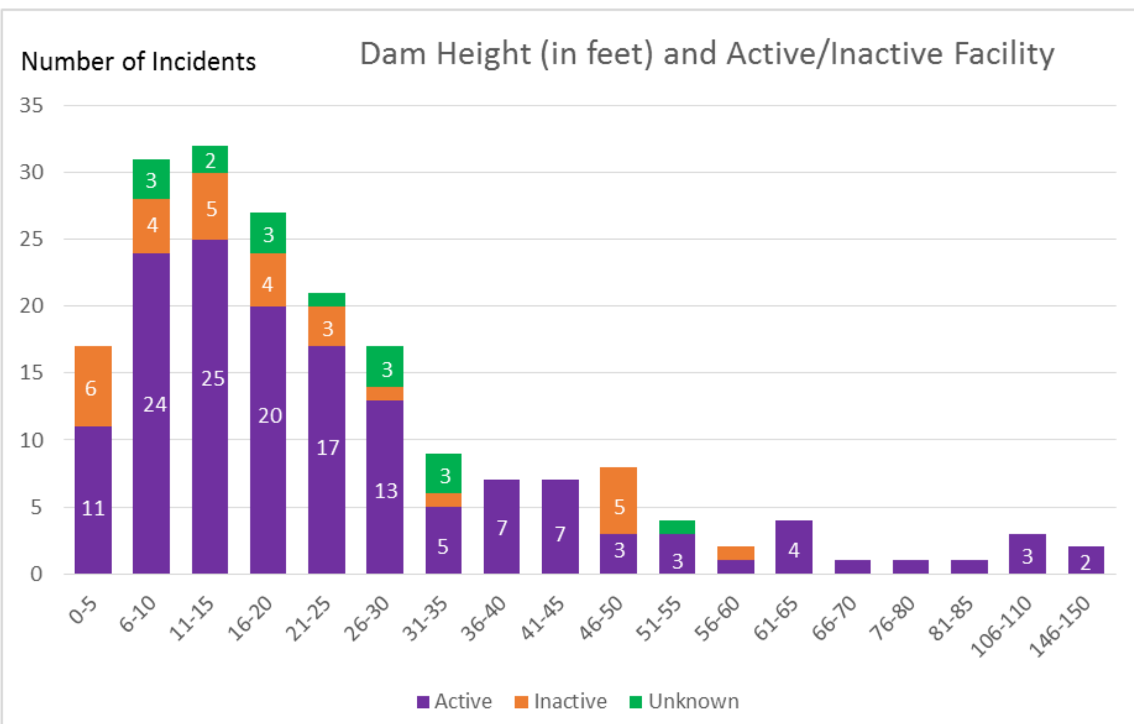

Figure 5. Dam height and active/inactive facility.

Incident Causes

The reported incident cause 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

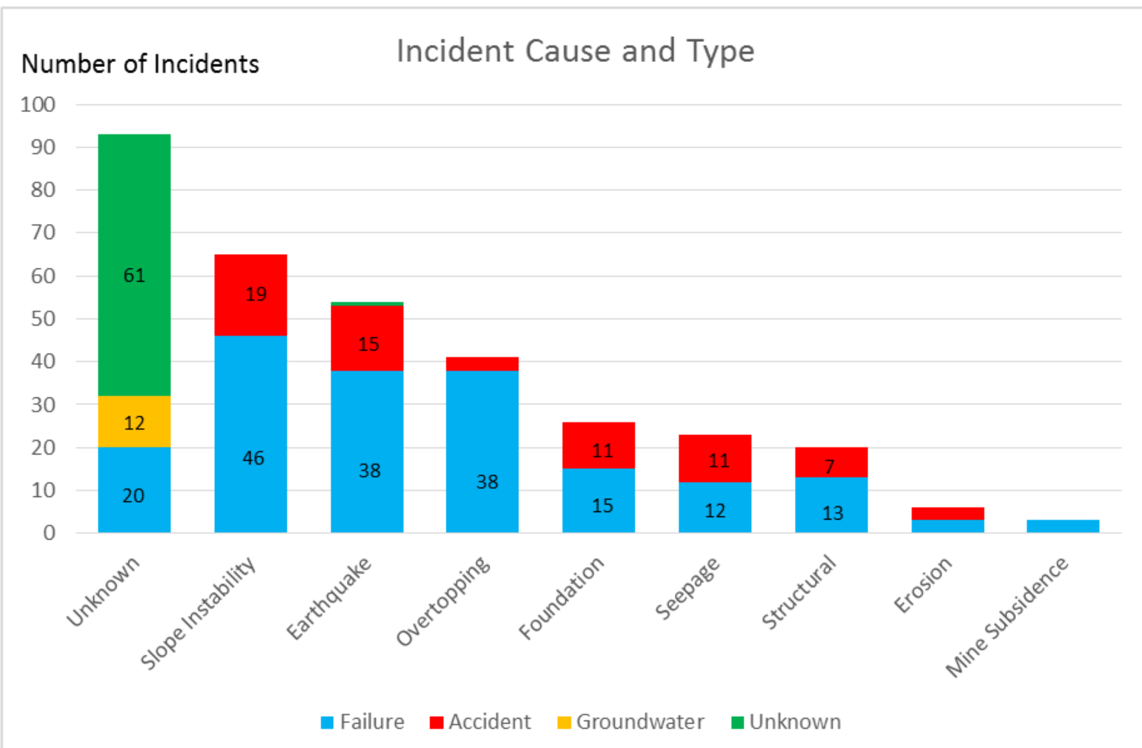

Figure 6. Incident cause and incident type.

For the incidents shown in Figure 6, slope instability, earthquake, and overtopping are the leading reported causes. Figure 6 also shows incidents where the cause is unknown.

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 tailings dams in active or operating conditions.

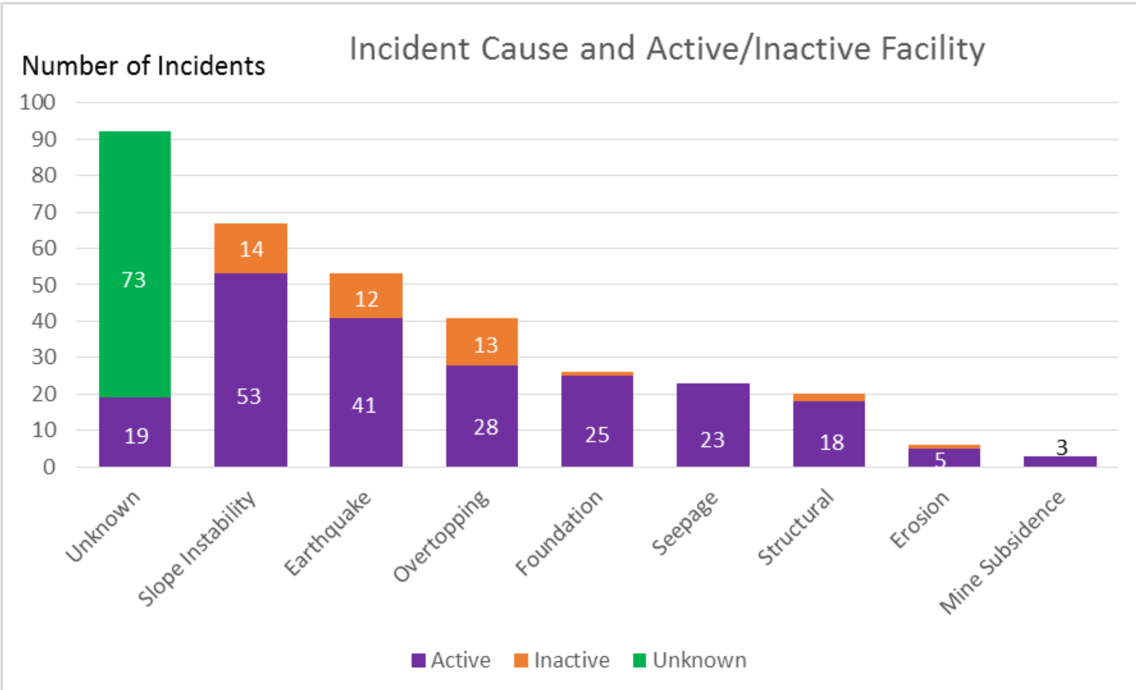

Figure 7. Incident cause and active/inactive facility.

<u>Incident Cause and Dam Type</u>

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 dam 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 placed over previously placed embankment 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. This type of construction results in subsequent embankment raises being placed over previously placed embankment material, natural ground, or tailings.

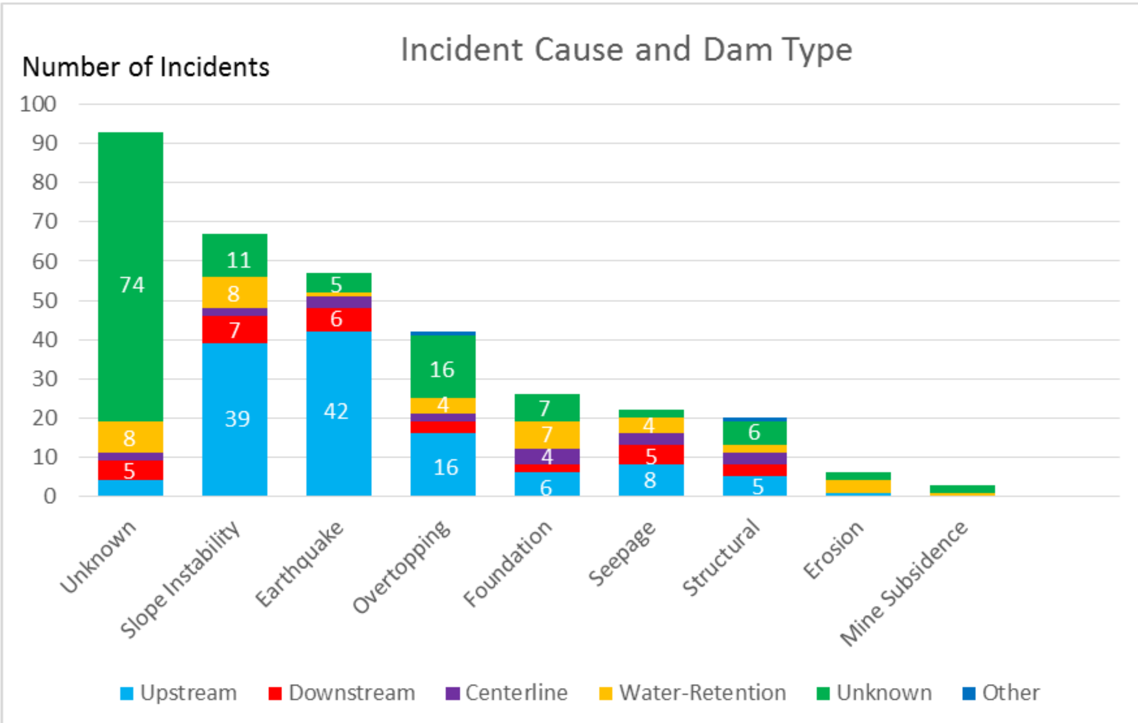

Figure 8. Incident cause and dam type.

The results of incidents with dam type in Figure 8 show that, while no dam type is immune from incidents, the majority of incidents are associated with upstream-constructed dams. This is due in part 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 most likely upstream-constructed dams.

For comparison, Figure 9 shows incident cause and dam type for more recent conditions (1976 through 2017). This data set reflects the period to time with better knowledge of dam construction, larger earthmoving equipment, and use of slope stability analyses.

However, the results in Figure 9 are similar to those in Figure 8. No dam type is immune from incidents, and the majority of incidents are associated with upstream-constructed dams. Many of the dams in the unknown column in Figure 8 are most likely upstream-constructed dams. The smaller number of incidents from earthquake and slope instability may reflect better geotechnical knowledge.

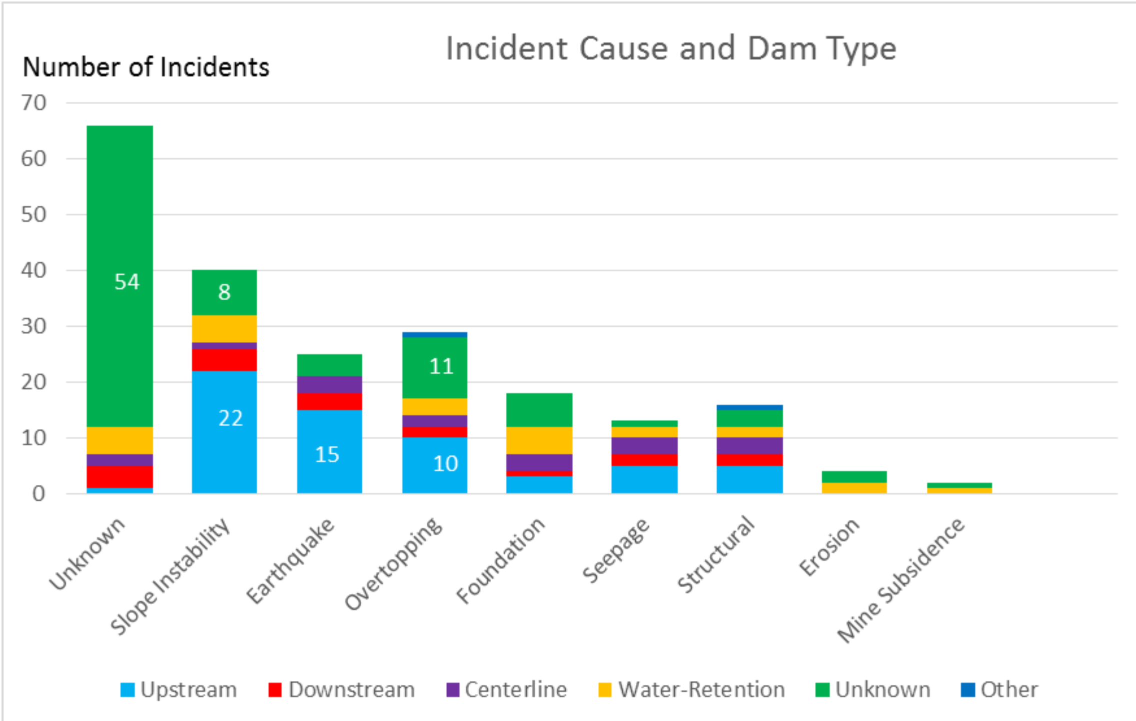

Figure 9. Incident cause and dam type, 1976-2017 time period.

CONCLUSIONS

From the data summarized in Figures 6 through 9, most of the reported incidents are associated with the water management aspects of the tailings dam, with incidents due to either water overtopping the dam or water seeping through the dam and affecting slope stability or causing erosion. Additional conclusions are summarized below.

Failure Frequencies

For 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 the introduction, the U.S. Bureau of Reclamation estimated an annual water-storage dam failure frequency of $6.2x10^{-4}$ (von Thun, 1985). Martin and Davies (2000) estimated an annual failure frequency for all water-storage dams of $1x10^{-4}$.

From Martin and Davies (2000), the estimated number of tailings dams in operation worldwide is approximately 3,500. From this number, estimated annual failure frequency is $1x10^{-3}$, and estimated annual incident frequency is $1x10^{-2}$ (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 in British Columbia. With seven failures over this period, the annual failure frequency is approximately $1.7x10^{-3}$, similar to the Martin and Davies (2000) world-wide failure frequency.

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, the tailings remain in place. Ponded water may be removed for recycling to the mill or by controlled discharge or water treatment and discharge. Emergency discharge of ponded water is possible, if there is a decant structure or spillway. Compared with water-storage dams, the ongoing embankment construction and water management aspects of tailings dams require careful consideration. 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, and public relations standpoints.

Water Management

Water management recommendations from IEEIRP (2015) and Wilson and Robertson (2015) include use of best available tailings technology, based on the following principles:

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 under a variety of operating conditions, depending on site conditions, topography, climate, and mill processes. These principles can be achieved with tailings ranging from slurried to filtered conditions, and for impoundments utilizing dams constructed by upstream, centerline, or downstream methods. The key factors are proper design, construction, operation, and monitoring to manage ponded surface water and tailings porewater.

As discussed in Wilson and Robertson (2015), elimination of surface water and promotion of unsaturated conditions is key to minimizing operational risks and well as transitioning the tailings from an impounding structure to a stable landform after closure. However, this principle is not consistent with environmental management strategy for maintaining chemical stability of sulfide-bearing tailings by saturation. The long-term water retention and stability aspects of a tailings dam with water-covered tailings must be considered for these conditions.

Summary

Methods to reduce the frequency of tailings dam incidents are summarized below.

- Managing tailings facilities to minimize ponded water, and maintain tailings surfaces to keep ponded water away from the tailings dams.

- Operating tailings facilities to optimize tailings densities by consolidation and drainage or by compaction or mechanical methods in the milling process (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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