

Trends in Tailing Dam Safety

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Abstract

Recent releases of tailing effluents and solids from containment facilities around the world, including Mary Spruitt (1994), Omai (1995) and Marcopper (1996), have heightened awareness that risks associated with tailing containment must be fully addressed during all phases of a facility life.

Recent studies by independent international organizations (United Nations Environment Programme (UNEP), 1996; United States Committee on Large Dams (USCOLD), 1994) have been carried out in response to these incidents in an effort to:

- identify the environmental and safety impacts most commonly encountered;
- determine the actual frequency of such incidents; and
- determine the environmental and human consequences of such incidents (UNEP, 1996).

Simultaneously, questions have also been raised by the international mining community as to:

- whether or not the expertise exists to safely build a tailing disposal facility using state of the art technology;
- and is the state of the art technology applied equally throughout the world in countries which rely on mining for development.

It is generally considered that most hydro-electric and water retaining structures are built to the best design standards available at the time. Data pertaining to the number and types of dam incidents associated with water retaining and hydro-electric dams was obtained from the USCOLD, Bulletin 99. This data was compared with the tailing dam failures noted above as well as the authors' experience with recent construction related projects throughout the world.

This paper summarizes these previous studies and provides insight into the trends concerning tailing dam safety.

1.0 Introduction

Recent releases of tailing effluents and solids from containment facilities around the world, including Mary Spruitt (1994), Omai (1995) and Marcopper (1996), have heightened awareness of the risks associated with tailing containment. The environmental and socio-economic impacts created by these incidents, as well as the increase in scrutiny and opposition with which new mining projects face, have prompted the North American mining community to ask several questions regarding the state of practice of tailing impoundment design, namely:

- does the technology exist to design and safely construct tailings dams?
- if so, are we designing to state-of-the-art standards?
- if the answers are yes, are we exporting this high level of technology and expertise offshore?

In order to answer these questions, we must first look at the history and evolution of tailing management methods (Section 2.0), assess the past and current state of practice of tailing impoundment design and construction (Section 3.0), and examine our performance record (Section 4.0).

2.0 Historical Development

Prior to the early part of this century, the technology for mining and smelting of metal ore was, by today's standards, primitive. The desired metals were separated from the crushed ore by gravity and the remaining tails were disposed of, usually in the nearest river or stream.

After the early 1900's, lawsuits arose over conflicts between mining companies employing direct discharge methods for tailing disposal on the one hand, and farming and newly flourishing communities on the other. This dispute over water supply and its contamination brought an end to the random discharge method of tailing management.

As tailings discharge possibilities became limited, mining companies started to contain tails on dry land using dams. An innovative method of constructing tailings dams was devised that required little engineered fill and used the waste material itself as the containment structure. This method, referred to as the upstream method of dam construction is shown schematically on Figure 1.

Initially a low starter dyke is constructed of local borrow material or mine waste rock. Tails are discharged off the top of the dyke forming a beach of sand which forces the pond supernatant away from the dam. A second dyke is then raised by borrowing from the beach and the dam is raised over the beach in subsequent stages.

However:

- upstream construction relies on a coarse grind to manufacture a coarse, free draining beach. Vick (1990) suggests that at least 40-60% of the tailing stream should be sand for this method to be successful;
- upstream dams are by their nature loose and saturated and are susceptible to liquefaction in areas of high seismicity;
- pond placement is the primary method of controlling the phreatic surfaces within the dams;
- pore pressure responses in the beach and slimes may control construction rates.

Nevertheless, dams of this type were the industry standard until the introduction of cyclones in the 1930's. Cyclones allowed additional segregation of the coarser fraction of the tails to create free draining sand shells which contained the much finer slimes. This initiated centreline construction which still used the waste materials to create the containment structure, but allowed finger drains and blanket drains to be placed in the downstream shell to collect and control excess construction and seepage water, and maintain low phreatic surfaces in the embankment. The cycloned sand shells can also be compacted using bulldozers, if necessary.

For centreline construction, an initial starter dyke is also built of borrow materials or waste rock, however, each subsequent raise is constructed directly above the initial berm as shown on Figure 1. Consequently, unlike the upstream method, no portion of the dam is constructed on unconsolidated tails.

By the start of the 1950's, large scale earthmoving equipment had been developed. This allowed larger tonnages to be mined economically which necessitated larger tailing containment areas and larger tailing dams to be constructed. The large capacity trucks allowed tailing dams to be built economically from borrow or waste with internal zones similar to water supply dams. These types of dams could be raised using either centreline or downstream methods of construction, as shown on Figure 1.

Seepage was generally not considered to be a major environmental issue in the early stages of tailing dam construction, although its influence on stability was acknowledged. Supernatant from flotation, cyanidation tailings were not considered to be particularly detrimental to the environment. However, as environmental impacts were identified and regulations tightened, methods of seepage control and the choice of dam construction methodology became more important. The recent concerns over Acid Rock Drainage (ARD) have led to the use of flooding as a popular method of mitigating ARD. However, flooding during operations limits the amount of beach available for supporting upstream or centreline construction techniques and virtually forces flooded dams to be built as downstream structures.

A historical summary of the methods of tailing disposal and the types of dams built over the past century is provided on Figure 2.

3.0 Design Standards

3.1 General

Many of the early tailing dam structures constructed in the 1920's through the 1940's were constructed on the basis of previous experiences with similar structures. However, not all were successful. In the 1950's, Karl Terzaghi introduced theoretical soil mechanics but it was not until the 1960's that these relationships were refined and became generally accepted throughout the mining community.

In the last 30 years, the science of soil mechanics has been applied to the design and construction of tailing dams, and the science has been refined using case histories which examine our mistakes. It is now recognized that there are several key factors that must be addressed in order to design a safe dam by today's standards (ICOLD, 1989). These include an understanding of the following items, which are discussed in more detail below:

- seismicity and earthquakes, and the corresponding response of the structures;
- hydrology and the prediction of flooding and water erosion;
- surface and subsurface seepage of contaminants from a chemical perspective;
- seepage control with respect to minimizing excess pore pressures and preventing solid migration (piping);
- plugging of filters and drains with fines and/or precipitates;
- tailings dam containment systems as a whole and not just the dams in isolation.

3.2 Seismicity and Ground Motion

Seismic response of earth embankments, foundations beneath the embankments, and the tailings behind embankments should be undertaken as part of a detailed design. ICOLD (1995a) note that key seismic stability considerations include:

- the magnitude and distance of design earthquakes and the design ground motions appropriate for the tailings storage site;
- the geotechnical properties of the tailings dam foundation and dam fill material;

- the design and construction of the dam;
- the potential inundation of and/or environmental damages to downstream areas in the event of dam incident or failure, and the selection of appropriate seismic design criteria;
- the selection of an appropriate method of seismic stability analysis; and
- the range of remedial measures available for enhancing the seismic resistance of an existing tailings facility and/or for mitigating potentially detrimental downstream effects that could result from its unsatisfactory performance.

Other works have summarized and recommended procedures for the design of dams under Earthquake Conditions (CEA, 1989).

3.3 Hydrology, Hydrogeology and Water Balance

ICOLD (1992) provides detailed methods for predicting floods, choosing probable maximum floods (PMF), and assessing downstream hazards. This ICOLD bulletin provides a survey of current practice and provides case histories of failures. Our understanding of stream and river flows, engineering geology and weather forecasting have all progressed in the last two decades allowing more flexible, sophisticated designs for tailing pond water balances to be undertaken.

3.4 Seepage Control and Drain Design

Ripley,(1988) has stressed that filter design is a critical part of dam design. Numerous people and design authorities are constantly revising filter design. However, Ripley notes that ‘The technology for design and construction of piping-proof filters is long established and proven’, (Ripley, 1988).

Filters must be designed: not to segregate; not to change in gradation; not to have apparent or real cohesion; be internally stable; have sufficient discharge capacity; and have the ability to control and seal a concentrated leak (ICOLD, 1994).

Typical filter design criteria include but are not limited to:

- retention criteria which have been developed to prevent migration of soil particles from adjacent foundation or fill materials. The classic Terzaghi criterion $D_{15} / d_{85} < 4$ (or < 5 US Army COE, 1986) generally addresses this requirement;
- permeability criteria which have been selected to allow the filter to accept seepage flows from adjacent foundation or fill materials without the buildup of excess hydrostatic pressure. Again, the classic Terzaghi criterion $D_{15} / d_{15} > 4$ (or > 5 US Army COE, 1986) generally addresses this requirement; and
- numerous other refinements have been published and a complete list of state-of-the-art practices for filter design is outlined in ICOLD, 1994.

3.5 Tailing Dam System Designs

The design of a tailing retention system which includes, but is not limited to all of the various components noted above is summarized by international organizations such as the International Commission on Large Dams (ICOLD), the Canadian Dam Safety Association (CDSA), USCOLD, and the Canadian Electrical Association (CEA). In addition, textbooks, guidelines, and technical supplements have been written to provide the geotechnical engineer with sound basis for the design of tailings facilities. Examples of recent texts include: *Planning, Design, and Analysis of Tailings Dams* by Vick (1990), and *Geotechnical Engineering of Embankment Dams* by Fell, MacGregor and Stapledon (1992).

4.0 Tailing Dam Performance Record

It appears, then, that we have the knowledge to design embankment dams, and in particular, tailing dams. But are all dams built equally? Failures have occurred that suggest that some are better than others.

Several studies have recently been completed to quantify and compile data identifying the causes of tailings dam failures. *Tailings Dam Incidents* (USCOLD, 1994) summarizes both anecdotal and published data available up until 1989. More recent data has been added and compiled in *Tailings dam Incidents 1980 - 1996* (UNEP, 1996).

The information in the above reports has been obtained from questionnaires, anecdotal information, and publicly available case histories. These data should be considered only partially complete as there is no single legislative body that records tailing dam statistics.

Furthermore, the data should be used cautiously to provide ‘failure statistics’ as there is no way to compare the number of tailing dam failures which have occurred and the total number of tailing dams built in any given area or time period.

Nevertheless, the data compiled by USCOLD (1994) and UNEP (1996) provide some insightful trends for tailing dam behaviour and this paper attempts to utilize some of the data to support the fact that tailings dams can be safely designed and built.

4.1 Statistical Analysis

Typical data recorded by USCOLD, (1994) include dam location, dam height, dam construction type, fill type, and the type of failure. For this paper, more recent data from UNEP, 1996 as well as personal experience and discussions with colleagues were added to the USCOLD summary.

The total number of recorded failures by dam type for both inactive and active tailing impoundments are shown in Figure 3. Upstream and unknown dam types dominate the graph. However, USCOLD correctly notes that these data alone cannot be used to infer the relative safety of centreline and water retention types because the proportional representation of these dam types in the overall population of dams is unknown. Upstream dams were built in larger numbers than all others, and centreline dams are not commonly built.

However, following a comparison of dam failure mechanisms versus dam types, USCOLD concluded that substantial differences between upstream-type dams and those of other types become evident:

- overtopping was most common in abandoned tailing facilities;
- slope stability and earthquakes were the most common cause of failure in dams utilizing upstream methods of construction;
- the failure modes for downstream constructed dams were relatively evenly distributed among all types;
- there was not enough data to reliably comment on the most prevalent failure modes for centreline dams;
- the most common failure mode for water retention type tailing dams was seepage, followed by overtopping and slope instability;
- in order of importance, slope instability, foundation, seepage and structural causes predominate for dam types other than upstream, and for these dam types earthquakes have not historically caused many incidents; and
- overtopping is of equal but lesser importance for all dam type categories.

Of all recorded failures, it is interesting to note that a significant hydraulic component accounted for 38 percent of the failures. The readers are referred to USCOLD for further discussion and analyses for various dam types.

5.0 Performance Relative to Other Structures

Given the history of tailing dam performance summarized above, the question still remains: are we designing and building using state-of-the-art?

Few people would dispute that organizations such as the United States Bureau of Reclamation (USBR), and our Canadian hydro-electric companies such as BC Hydro, Ontario Hydro, or Quebec Hydro are using state-of-the-art practices when constructing large water impoundment dams. International hydro-electric companies located in Peru, Brazil,

and Chile are all held in high regard for using state-of-the-art practices. However, some of these companies have constructed dams that have had problems, or are thought by some to be less than ideal.

The BC Hydro WAC Bennet dam is a recent example of a dam that was constructed to state-of-the-art standards, yet still developed sinkholes on the crest and prompted a dramatic lowering in the reservoir. The cause of the sinkholes appear to be the result of the migrating of fines within the core of the dam. The Teton dam in Idaho failed catastrophically during the initial filling of its reservoir in 1976. The piping failure of the dam was caused by, “...the many combinations of unfavourable circumstances inherent in the situation (which) were not visualized, and because adequate defences against these circumstances were not included in the design” (Dunnicliff et al, 1984). Despite their apparently superior reputation, are water supply dams and tailing dams so different after all?

A summary of behaviour of water and hydro-electric dams is provided in *Dam Failures Statistical Analysis* (ICOLD, 1995b). For this paper, the ICOLD data on water supply dams was compared to the previously discussed summary on tailing dams. Although every attempt has been made to provide a thorough database, the data compiled in each of the reports listed above, and that summarized in this paper are not complete. Therefore, any statistical conclusions made from these data are not definitive. Nevertheless, convincing trends are apparent.

Figure 4 shows a plot of the total number of failures reported from all countries in ten year increments for both tailing dams and water supply dams. Prior to the 1940's, there were very few reported failures of tailings dams. Either few of the existing dam failures were documented, or the total number of failures was small. From the 1940's to the 1970's, the number of failures for both tailing dams and water supply dams increased substantially. It could be hypothesized that the rise in number of failures in the 1950's to 1960's may be due to the increasing size of earthmoving equipment allowing larger dams and faster

construction. This trend peaks in the 1960's for water supply dams, and the 1970's for tailings dams, and has been generally decreasing since that time. The decreasing trend following the peak may reflect our expanding knowledge and the subsequent application of soil mechanics principles to the design and construction of dams, as well as the improvements in construction methods and techniques.

It should be noted that the data has not been normalized for the total number of tailing and water supply dams, as this information was not available. However, the general trends in the data for both water supply dams and tailing dams are comparable and worth noting. The overall behaviour of the two different structure types are, in general terms, very similar.

A plot of tailing and water supply dams failures versus dam height indicates that more small dams have failed than large dams. However, there are significantly more small dams than large dams for both water supply and tailing dams (USCOLD, 1994; ICOLD, 1995b). Figure 5 shows a plot of water supply dam data showing the total number of failed dams of a certain height interval, and the total number of dams of a certain height interval, normalized for the total number of failed dams and total number of dams respectively, (ICOLD, 1995b). This shows that the ratio of failed dams to existing dams for each height interval is approximately the same, and that no height interval appears to be more susceptible to failure than another.

The total number of tailing dams is not available to allow us to present a similar plot for tailing dams. However, the ratio of the number of failures of a certain height interval over the number of failed dams for both tailing and water supply dams are almost the same as shown on Figure 6. Based on the results in Figures 5 and 6, it is hypothesized that no single height interval of tailing dams is more susceptible to failure than any other.

Finally, in the last 70 years, there have been over 1000 reported fatalities as a direct result of flow failures of tailing dam and related incidents for coal waste dumps (Vick, 1997).

However, one single event involving the failure of water supply dams took the lives of an estimated 86,000 to 230,000 people in August of 1975 in China. The failure of the two largest dams, the Banqiao and Shimantan, as well as the failure of 60 other dams in this event, caused by a one in two-thousand year typhoon over shadows the entire failure history of tailing dams (Tuxill, 1996).

Excluding the soviet block and China, total fatalities as a direct result of water supply dam failures during the period of 1900 to 1980 have been estimated to be in excess of 8,000 (Jansen, 1983).

Given the similarity in the general trends for failures of water supply dams and tailing dams, it would appear that both types of dams are being built to at least the same state-of-the-art standard.

Are we exporting this level of expertise when developing mining projects in overseas and third world countries. Figure 7 shows the total number of reported failures in each of several countries. Vick (1997) states that, "Fatal incidents have occurred from tailings of many ore types and in both developed and less-developed countries. No segment of the industry or location has been immune."

Apart from the anomalously high number of failures reported in the United States, there does not appear to be a well defined trend that would imply that the quality of design is not applied evenly throughout the world. The data presented in Figure 7 is not normalized for the number of dams in each country.

6.0 Conclusions

It would appear that tailing dams, even though they have received a large amount of attention in the last 5 years, are behaving comparably with water supply dams in terms of failures and accidents that have captured the public attention. If we accept the hypothesis that hydro-electric dams and water supply dams are built to state-of-the-art levels, then it appears not unreasonable to conclude that tailings dams are built to the same high standards.

However, the authors are not advocating complacency. Failures still occur and environmental impacts do require mitigation. There is finite probability that some failures will occur regardless of the use of sound engineering and strict adherence to engineering principles, and possibly risk assessment methodologies can assist in lowering the failure rates even more. There is widespread acceptance of the merits of risk management and the trend towards adopting it is irreversible in western society. Many provincial, state and federal regulatory agencies are requesting modern risk-based approaches to hazard management in the early stages (Vick 1996).

Over the last few years, some mining companies have become proactive and have adopted management strategies to deal with the risks of tailing containment systems. The risk assessment is a means for rationalizing decision making with respect to tailing dam design in current times of financial constraints and limited budgetary resources. While risk assessments do not replace sound engineering, they do allow a formalization of the design process and possibly highlight some problems which might otherwise go undetected.

There has been little in the way of published statistics for tailings impoundments so the notion of relative risks is generally adopted. However, there is also a strong pressure from both regulators and owners to define acceptable risks. It is hoped that compilation of the data for existing and future work such as presented in USCOLD 1994 and in this paper, will assist in the preliminary quantification of acceptable risks.

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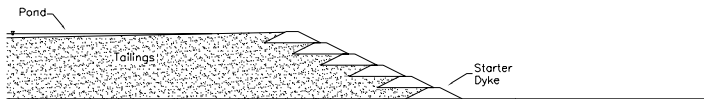
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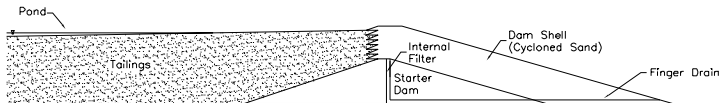
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Figure 1 – Schematic of Various Methods of Construction

Upstream Construction



Centreline Construction



Downstream Construction

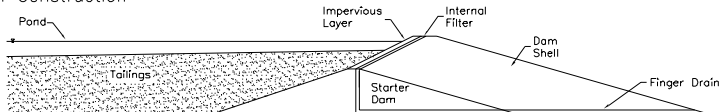
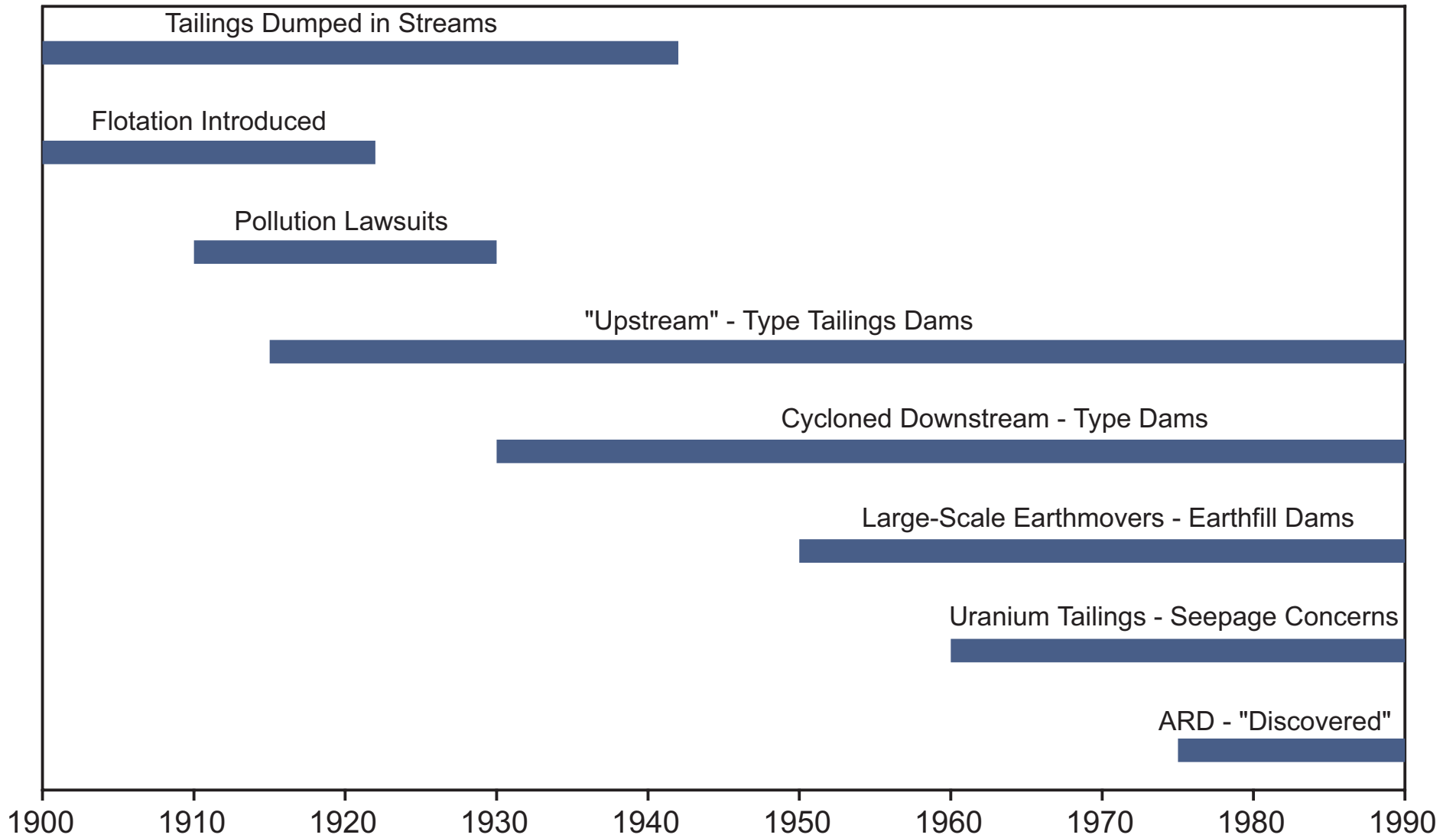
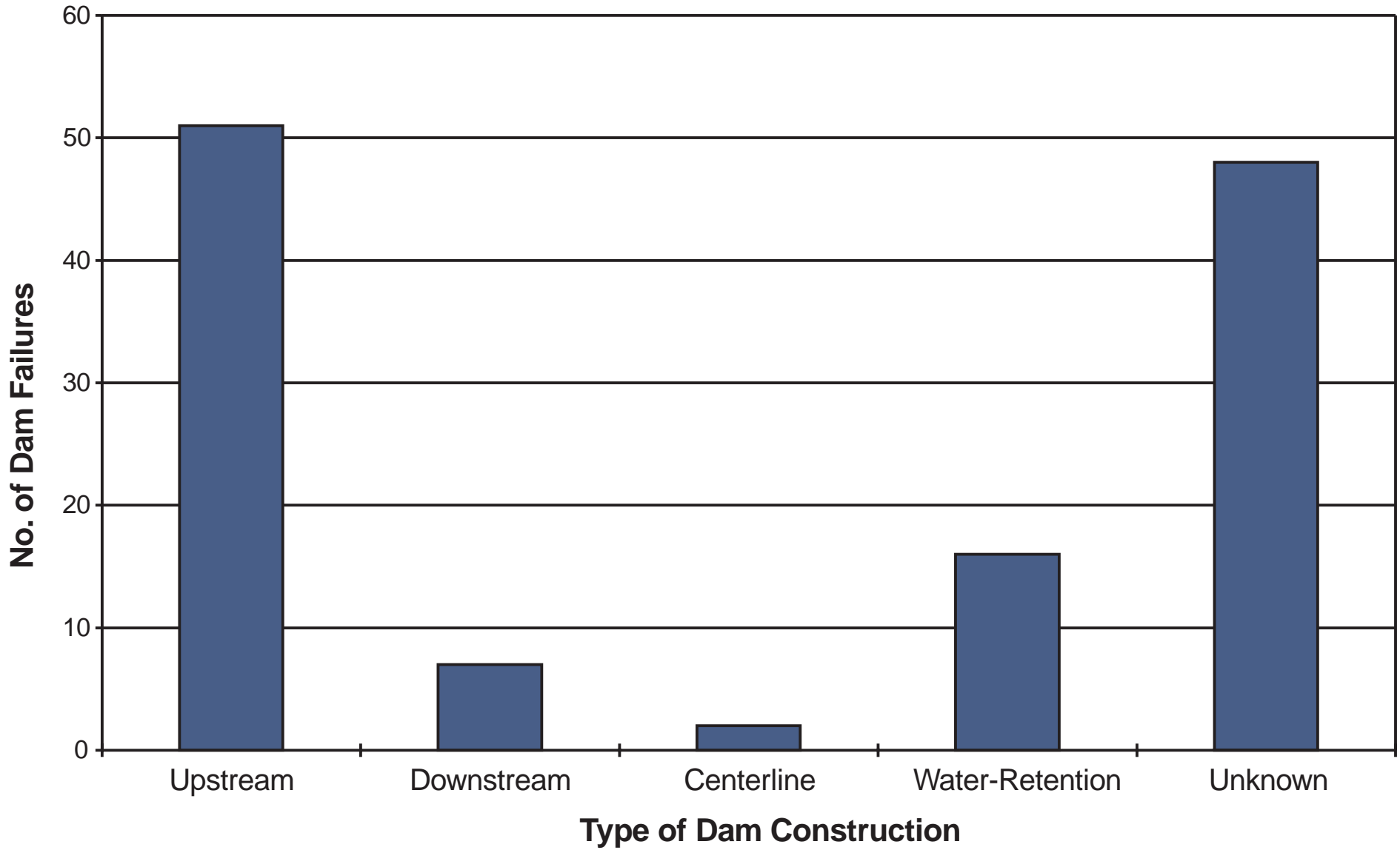


Figure 2 - Historical Evolution of Tailings Management



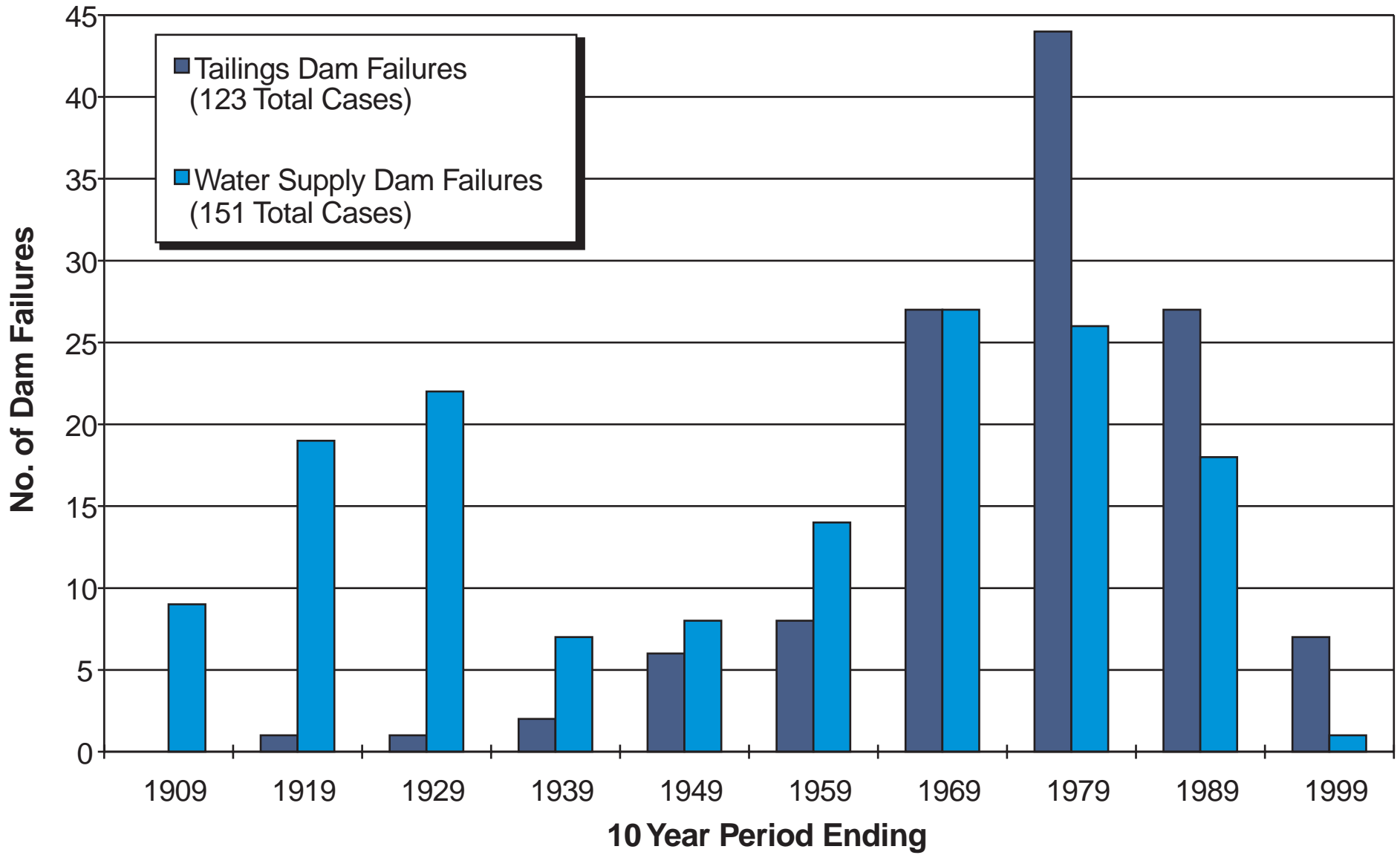
(VICK, 1995)

Figure 3 - Tailings Dam Failures by Dam Type
(Active and Inactive)



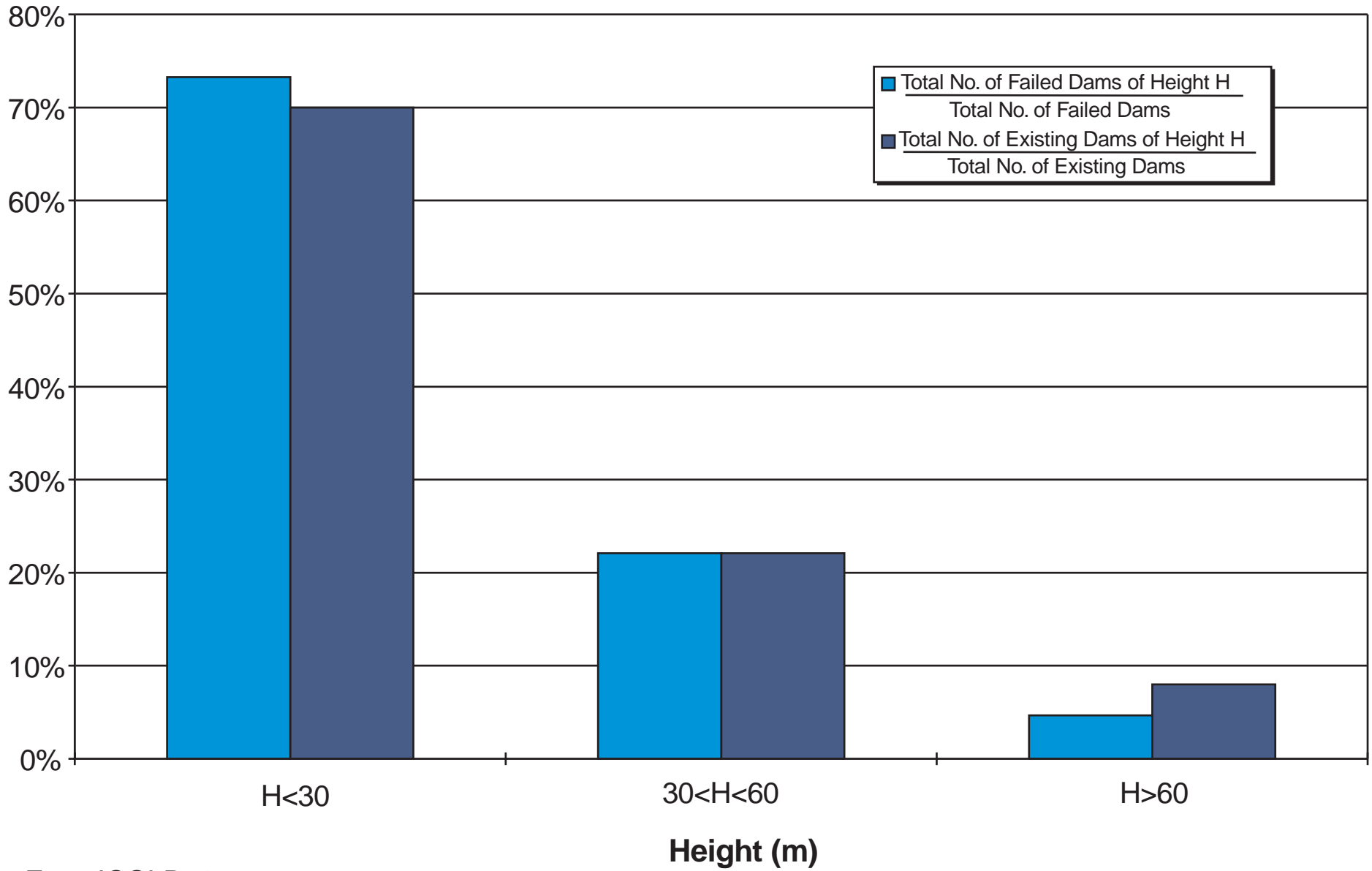
(USCOLD, 1994; UNEP, 1996)

Figure 4 - No. of Water Supply and Tailing Dams (Active and Inactive) Failures vs. Time



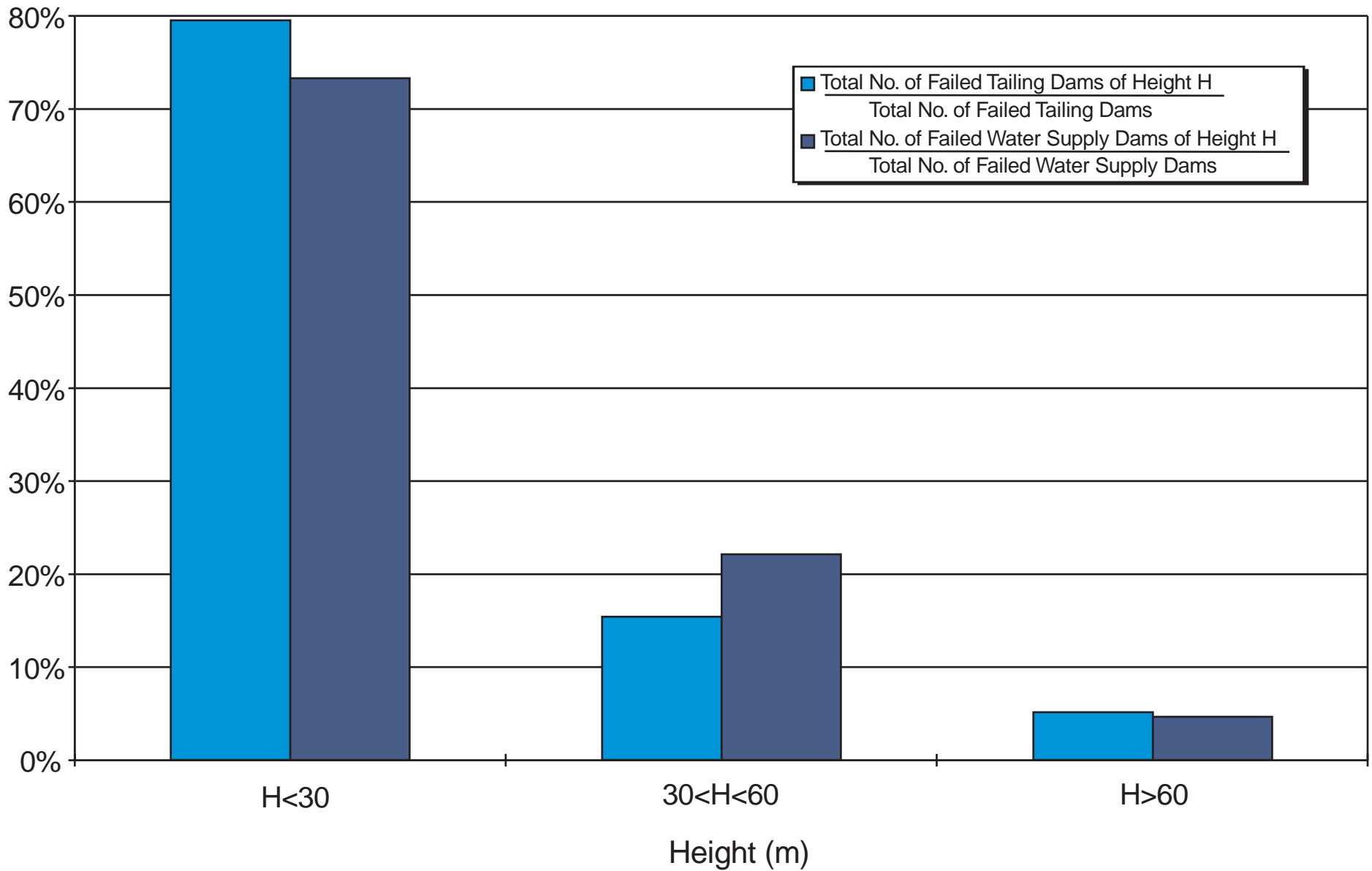
(USCOLD, 1994 and UNEP, 1996)

Figure 5 - Water Supply Dam Failures vs. Height



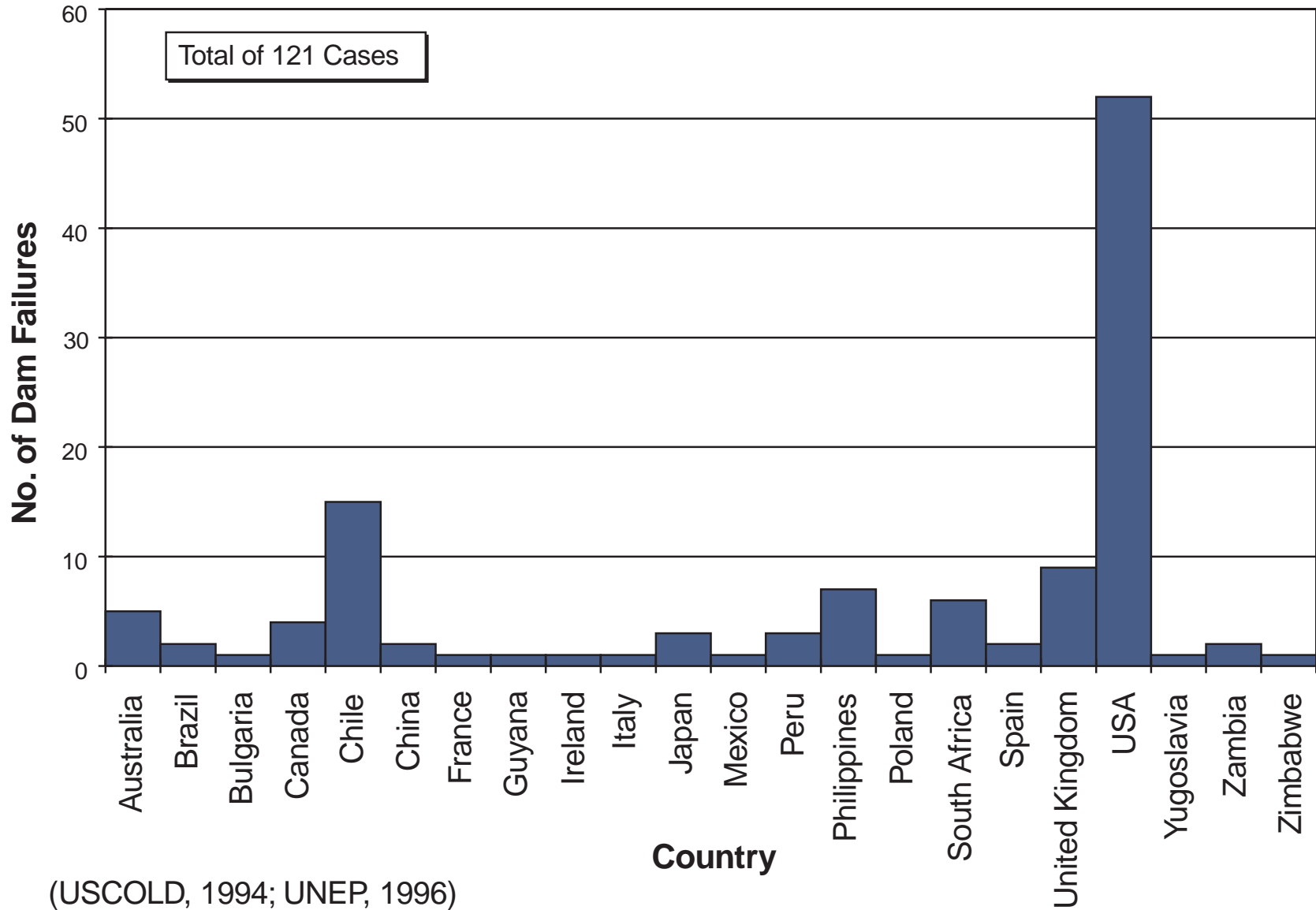
From ICOLD, 1995

Figure 6 - Water Supply Dam and Tailings Dam
(Active and Inactive) Failures vs. Height



ICOLD, 1995; UNEP, 1996; USCOLD, 1994

**Figure 7 - Tailing Dam Failures by Country
(Time Period 1917-1996)**



(USCOLD, 1994; UNEP, 1996)