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Contents

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ABSTRACT: Tailings management often represents the most significant environmental challenge associated with mining projects. A spate of recent and well-publicized incidents involving tailings impoundments has placed the mining industry in general, and those responsible for tailings impoundment design and safety in particular, under intense scrutiny. Given the lack of environmental stewardship in historic mining operations, objective and rational scrutiny is deserved, constructive, and should be welcomed. Significant advances have been made on many fronts to develop and implement the principles underlying effective and responsible stewardship of tailings facilities. Learning the lessons readily available from the failure database has largely facilitated development and implementation of these principles. International organizations, mining industry associations, and individual mining companies themselves, have been very proactive in recent years in advancing the state of practice for stewardship of tailings facilities. In particular, the environmental, financial, and political consequences of well-publicized failures have made it clear to the mining industry that its own best interest demands safe tailings management practices.

Evolving advances in stewardship of tailings facilities can be classed under three broad categories: management aspects, tailings handling and treatment technologies, and mineral processing technologies and alternatives. This paper discusses the key advances being made under each of these three categories, with particular emphasis on management aspects, considered by the authors to be of the utmost importance and the category in which the greatest strides have been achieved in recent years. The principles underlying appropriate design of tailings facilities, and of responsible stewardship of tailings facilities, are well understood. It remains only for the mining industry to apply these principles in a consistent manner for all projects. The continued growth of the failure database indicates that additional effort in this regard is required.

1 INTRODUCTION

Tailings storage facilities typically represent the most significant environmental liability associated with mining operations. They have been in the news frequently in recent years for unfortunate reasons, as a result of a series of well-publicized failures subjected to rapid and widespread reporting in the media. These recent failures, together with previous ones, have put the mining industry under increasing pressure and scrutiny in regard to its environmental practices in general and the safety of tailings impoundments in particular. The recent and previous failures and "incidents" with tailings management facilities have also served to strengthen the hand of those who argue that the mining industry in general, and the way the industry manages its waste products in particular, are incompatible with protection of the environment, particularly with regards to leaving a negative legacy for future generations. This scrutiny, while more intense in recent years, is nothing new, as evidenced by the quotation below:

> *"The strongest argument of the detractors of mining is that the fields are devastated by mining operations…further, when the ores are washed, the water used poisons the brooks and streams, and either destroys the fish or drives them away…thus it is said, it is clear to all that there is greater detriment from mining than the values of the metals which the mining produces"* (Agricola, 1556).

This quotation, over 400 years old, has a central theme often repeated today in spite of the benefits that mining has provided and continues to provide society. The mining industry's only valid defense against such criticism must be demonstration, not verbal reassurances, that its tailings facilities are well-designed, well-managed, and can be securely closed, reclaimed and maintained in a non-threatening state. For the most part this is indeed the case, but it is the failures, rather than the successes, that garner the publicity, all of it negative. The mining industry, like nearly all other industries, is saddled with a checkered past with regards to protection of the environment. The industry, its critics, and society, which through its consumption patterns implicitly value the commodities the industry produces, must acknowledge the past but focus on the future. It is incumbent on the industry to publicize and to demonstrate the many advances being made in responsible stewardship of tailings facilities, advances that have been largely spearheaded by the industry in response to public and regulatory pressure, in addition to the industry's own self-interest.

Stewardship is defined for the purposes of this paper as "taking care of". A tailings facility must be appropriately "taken care of" in all aspects of design (conceptual through detailed), construction, operations, inspection, surveillance, review, and management (corporate policies, training, roles and responsibilities, documentation and reporting, etc.) in seeing a tailings facility through from conceptual design to closure. Stewardship also embraces the mill process itself, as that is where tailings management really begins. This paper will focus primarily on those aspects of stewardship of facilities that apply during tailings facility operation. Closure and reclamation issues, while of critical importance, are not addressed except in the recognition that all facets of tailings stewardship, including pre-feasibility study stages, must be carried out with the end (i.e. closure) in mind. All tailings facilities must be completed, and maintained, in a manner that assures their safety and integrity (physical and environmental) for the closure period, which is perpetuity. Perpetuity is a long time.

Over the past several years, initiatives have been taken on a variety of fronts to improve the stewardship, and therefore the safety, of tailings impoundments. Evolving tailings handling technologies and mill processing alternatives offer another avenue for achieving responsible stewardship and sustainable development. Design practice for tailings dams continues to evolve and improve. Purely technical design aspects are extensively covered in the geotechnical literature and are not the subject of this paper, which instead focuses on relatively recent design practice developments, and on initiatives, related to the safe management of tailings facilities. Good stewardship involves checks and balances, and auditing and quality assurance procedures that should detect, and correct, design and/or operational deficiencies before they manifest into incidents. No stewardship will be sufficiently robust to cover for all potential design and/or operational flaws, and no design is sufficiently robust for the most negligent stewardship.

2 BACKGROUND AND HISTORY OF TAILINGS DAMS

To understand the future of stewardship of tailings facilities, it is first necessary to understand the past. The reader is referred to USCOLD (1994), from which much of the following account has been drawn.

Mining has been carried out in some form for at least 5 000 years. In forms more similar to modern mining, crude millstone crushing and grinding of ore were initially practiced in the New World in the 1500's, and continued through the mid-1800's. The largest change over those centuries was the introduction of steam power, which greatly increased the capacity of grinding mills and hence, the amount of barren by-product (tailings) produced.

Minerals of economic interest were initially separated from crushed rock according to differences in specific gravity. The remaining tailings were traditionally routed to some convenient location. The location of greatest convenience was often the nearest stream or river where the tailings were then removed from the deposition area by flow and storage concerns were largely eliminated. Later in the 1800s, two significant developments that changed mining dramatically were the development of froth flotation and the introduction of cyanide for gold extraction.

Flotation and cyanidation greatly increased the ability to mine low-grade ore bodies, and resulted in the production of still larger quantities of tailings with even finer gradation. However, tailings disposal practices remained largely unchanged and, as a result, more tailings were being placed and transported over greater distances into receiving streams, lakes and oceans.

Around 1900, remote mining districts began to develop and attract supporting industries and community development. Conflicts developed over land and water use, particularly with agricultural interests. Accumulated tailings regularly plugged irrigation ditches and “contaminated” downstream growing areas. Farmers began to notice lesser crop yields from tailings-impacted lands. Issues with land and water use that led to the initial conflicts then led to lawyers discovering the fruitful field of mine waste management and litigation in both North America and Europe flourished. Legal precedents gradually brought an end to uncontrolled disposal of tailings in most of the western world, with a complete cessation of such practices occurring by about 1930. However, these practices still remain in many areas in the developing world where it is argued by proponents of such practices that this allows these jurisdictions to “catch up” using the same environmental stewardship those in the western world practiced the past two centuries..

To retain the ability to mine, industry fostered construction of some of the first dams to retain tailings. Early dams were often built across a stream channel with only limited provisions for passing statistically infrequent floods. Consequently, as larger rainfalls or freshet periods occurred, few of these early in-stream dams survived. Very little, if any, engineering or regulatory input was involved in the construction or operation of early dams.

Mechanized earth-moving equipment was not available to the early dam builders. As a result, a hand-labour construction procedure (the initial upstream method) was developed. A low, dyked impoundment was initially filled with hydraulically-deposited tailings, and then incrementally raised by constructing low berms above and behind the dyke of the previous level. This construction procedure, now almost always mechanized, remains in use at many mines today.

The first departure from traditional upstream dam construction likely followed the failure of the Barahona tailings dam in Chile. During a large earthquake in 1928, the Barahona upstream-constructed dam failed, killing more than 50 people in the ensuing, catastrophic flowslide. The Barahona dam was replaced by a more stable downstream-raised dam, which used cyclones to procure coarser-sized material for dam construction from the overall tailings stream. By the 1940’s, the availability of high-capacity earthmoving equipment, especially at open-pit mines, made it possible to construct tailings dams of compacted earthfill in a manner similar to conventional water dam construction practice (and with a corresponding higher degree of safety).

The development of tailings dam technology occurred on an empirical basis, geared largely to the construction practices and equipment available at the time. This development was largely without the benefit of engineering design in the contemporary sense. Nonetheless, by the 1950’s many fundamental dam engineering principles were understood and applied to tailings dams at a number of mines in North America. It was not until the 1960’s, however, that geotechnical engineering and related disciplines adopted, refined, and widely applied these empirical design rules. The 1965 earthquake-induced failures of several tailings dams in Chile received considerable attention and proved to be a key factor in early research into the phenomenon of liquefaction. Earthquake-induced liquefaction remains a key design consideration in tailings dam design.

Issues related to the environmental impacts from tailings dams were first seriously introduced in the 1970’s in relation to uranium tailings. However, environmental issues related to mining had received attention for centuries. Public concerns about the effects of acid rock drainage (ARD) have existed for roughly 1,000 years in Norway. Public concerns were similarly expressed hundreds of years ago in Spain and in Greece. Mine workings developed in Roman times in Spain continue to produce ARD over 2,000 years later.

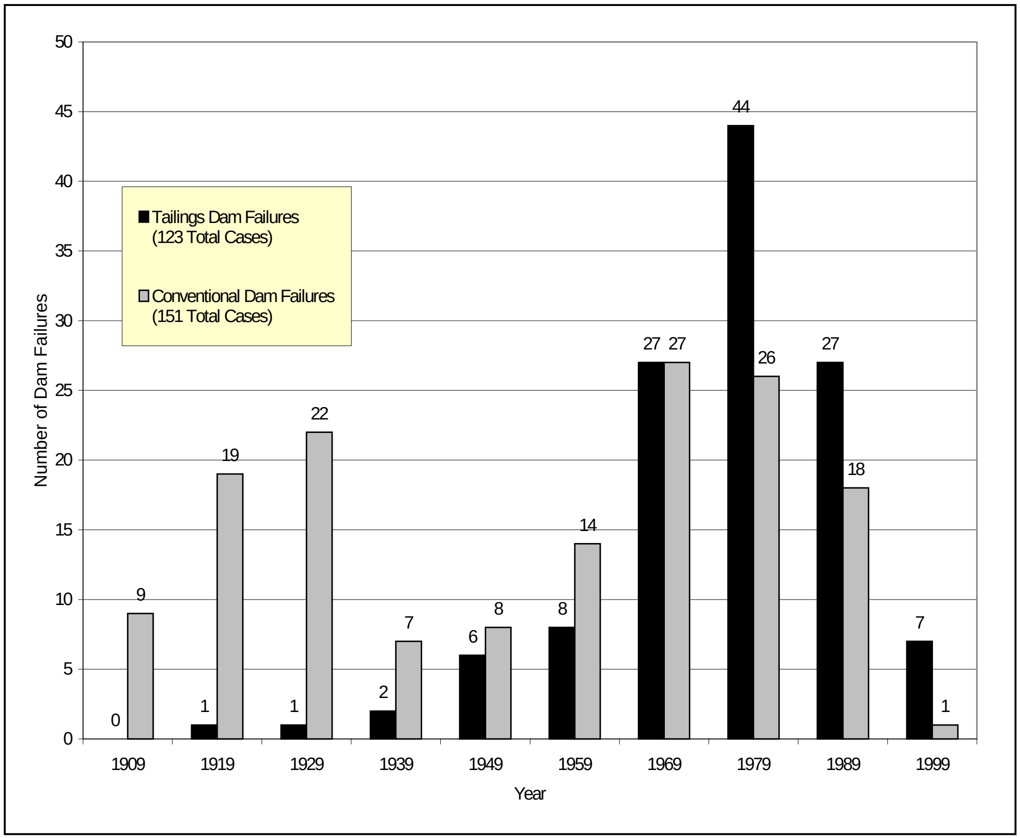
In the early 1970’s, most of the tailings dam structural technical issues (e.g. static and earthquake induced liquefaction of tailings, seepage phenomena and foundation stability) were fairly well understood and handled in designs. Probably the only significant geotechnical issue not recognised by most designers was the static load induced liquefaction (e.g. the reason for many previously "unexplained" sudden failures). However, issues related to geochemical stability were not as well recognised, and tailings impoundments were rarely designed and operated with reclamation and closure in mind.

Over the past 30 years, environmental issues have grown in importance as attention has largely turned from mine economics and physical stability of tailings impoundments to their potential chemical effects and contaminant transport mechanisms. Physical stability issues have remained at the forefront, as recent tailings dam failures have drawn unfortunate publicity to the mining industry, with severe financial implications in many cases (Davies, 2001). A significant tailings impoundment failure will almost certainly have a direct cost in the tens of millions of dollars and indirect costs, including devaluation of share equity, often many times the direct costs. In all of the tailings dam failure cases, a few examples of which are noted later in this paper, relatively simple, well-understood structural failure mechanisms were found to be at fault in causing the incidents. In each case, mechanisms described in a landmark paper by Klohn (1972) were the main technical contributors to failure. That such well-understood mechanisms continue to underlie tailings dam failures illustrates that stewardship practices continue to be lacking in too many cases. The necessary knowledge to prevent such failures has existed for decades, but it is not yet being used, or appropriately used, in all cases.

3 UNIQUE FEATURES OF TAILINGS DAMS

With the benefit of the background discussion above, it is worthwhile to consider the unique features of tailings dams, in the context of a comparison to conventional water-retaining dams. This comparison is particularly valuable given that Figure 1, comparing failure rates of conventional and tailings dams, shows a positive trend for conventional dams, and a markedly less positive trend for tailings dams. Why is this so?

Figure 1. Tailings Dam Failures vs. Conventional Dam failures (ICOLD, 1995)



Stewardship practices for conventional dams are well-established. Some aspects of these practices are applied to tailings dams, but many are not. This is as it should be, since tailings dams differ significantly in many respects from conventional dams. The key differences between tailings dams and conventional dams, and the significance of these differences, are discussed in detail by Szymanski (1999), and are summarized below.

- Tailings dams are typically constructed in stages or on a continuous basis over many years, while conventional dams are usually constructed in a single stage in a short time period. As a result, the condition of the tailings facility is continually changing, and so its safety must be continually re-evaluated. In some respects, this renders tailings dam stewardship more onerous than is the case for conventional dams. A steady state condition is not achieved until after the mine operation has ceased.
- Tailings dams are in many instances constructed on a continuous basis by mine operators, who are in the business of extracting wealth from the ground, not in dam-building. There is an understandable tendency for mine operators not to focus on tailings dams.
- Conventional dams are typically owned by a state, province, public utility company or water resource authority. These dam owners typically have substantial resources at their disposal, and have a different relationship with the public in that the public benefits directly from the dams. Contrast this to tailings dams, which are owned and operated by mining companies, with the public perceiving no direct benefit from the tailings dam. As a result, mining companies tend to be “punished” more severely than conventional dam owners when failures do occur.
- Conventional dams are viewed as an asset. As a result, their construction, operation, and maintenance receives a high standard of care and attention from owners, who often retain in-house dam engineering expertise. Contrast this to tailings dams, which have until recently been viewed by their owners as an unprofitable, money-draining part of the mining operation. The significance of this aspect is that with such attitudes a mining operation would be naturally less inclined to expend effort in the management of its tailings facility than the owner of a conventional dam. This is changing, however, with the acceptance that resources applied to tailings facility stewardship represent an essential investment, and not a cost.
- Mining companies typically do not retain in-house dam engineering expertise, relying instead on consultants. This introduces another player into tailings facility stewardship, together with the potential for lack of good and clear communication, and lack of project continuity.
- Tailings dams typically retain materials (solids and water) that would be considered “contamination” if released. The need to prevent release of these materials in terms of environmental impact is not a consideration for conventional dams, and represents an aspect in which tailings dam design and performance requirements differ significantly from conventional dams.
- In terms of how a tailings facility affects future generations, perhaps the most significant difference between the two types of dams relates to their lifespan. Conventional dams generally do not need to be designed to last forever, as they have a finite life. Tailings dams have a closure phase as well as an operational phase. The have to be designed and constructed to last “forever”, and require some degree of surveillance and maintenance long after the mining operation has shut down, and generation of cash flow and profit has ceased.

The common thread of each of the above differences is that they demand application of unique, and comprehensive, stewardship practices for a tailings facility throughout its long service life. Furthermore, since many tailings dams are unique, there is no “off the shelf” approach suitable for every tailings facility, although certain basic elements should be common to all.

4 TAILINGS DAM FAILURES – A BRIEF REVIEW AND PERSPECTIVE

4.1 *Tailings Dam Instability Incidents*

The intent of this paper is to focus on the future of tailings facility stewardship, and to review stewardship practices that lead to success in tailings management and compliance with the objectives of sustainable development. Even so, it is fact that the mining industry, like most other fields of human endeavor, learns as much if not more from failure than from success. It is therefore worthwhile to review failures and to understand what those failures are telling us.

Tailings dam failures are, despite the recent publicity, relatively infrequent events that are unrepresentative of modern mining industry success in safe tailings disposal, though the current rate of failures remains unacceptably high. The reporting of such events is incomplete and often biased, and there is no worldwide database of failures. This is illustrated by Figure 2, which appears to suggest that the United States has experienced the most tailings dam failures, but what it really indicates is that the United States has had the best means of reporting and documenting failures. For example, the authors have collective documentation on more than a dozen “failures” in Canada alone, three more in Central America, and another five in South America (using the USCOLD/UNEP definition of failure) that do not show up on Figure 2. This is undoubtedly the case for other jurisdictions. The database is further biased in that it does not account for the number of tailings dams in each country.

Figure 3 plots the frequency of significant tailings impoundment failures against time. This plot shows a rapid increase in the number of reported failures through the 1960’s and 1970’s, probably reflecting increased reporting, increased and larger scale mining developments and larger tailings impoundments, raised at increasing rates. This period also corresponds with the rapid development of tailings dam design as a formal engineering discipline. This same period saw a growing realization on the part of the mining industry that, with tailings impoundments becoming ever more larger and having to meet increasingly stringent environmental performance standards, they required a considerable degree of attention to maintain their safe operation. These two factors probably underlie the possible trend of decreasing frequency of failures since 1980. Unfortunately, however, no fewer than 6 significant failures occurred between July 1999 and October 2000, a rate equivalent to 40 to 50 failures per decade. At the beginning of the new millennium, the mining industry appears to be at a crossroads in terms of its stewardship of tailings facilities and the environment. It may also be at a crossroads in its efforts to convince the public that mining is an industry compatible with safeguarding of the environment.

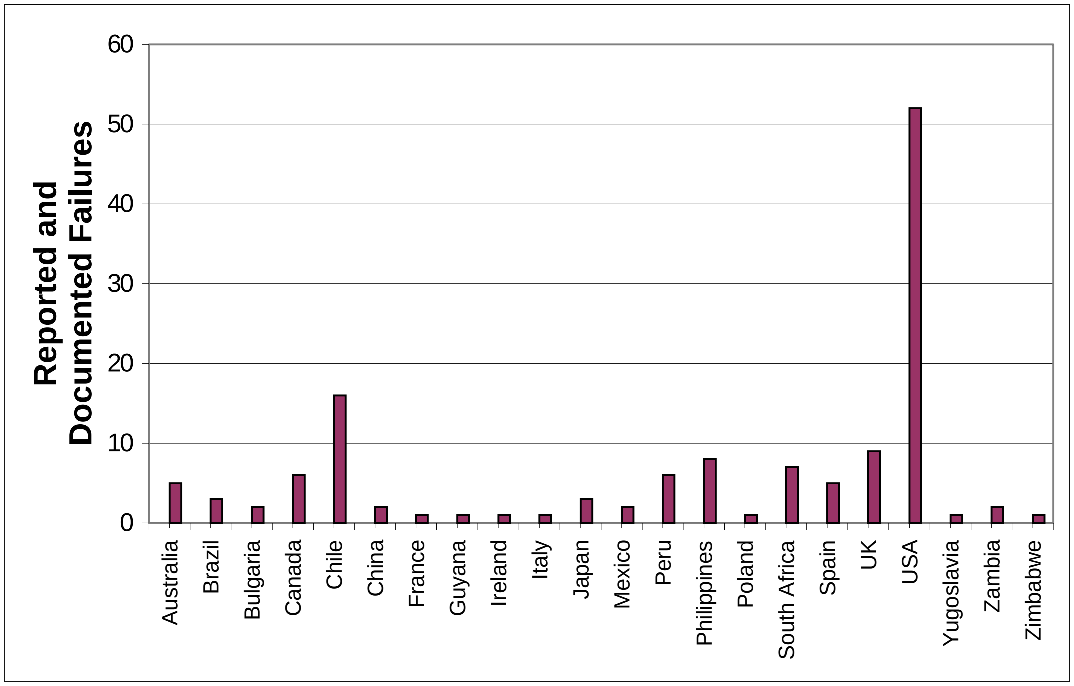


Figure 2. Tailings Impoundment Failures by Country (USCOLD, 1994 and UNEP, 1996)

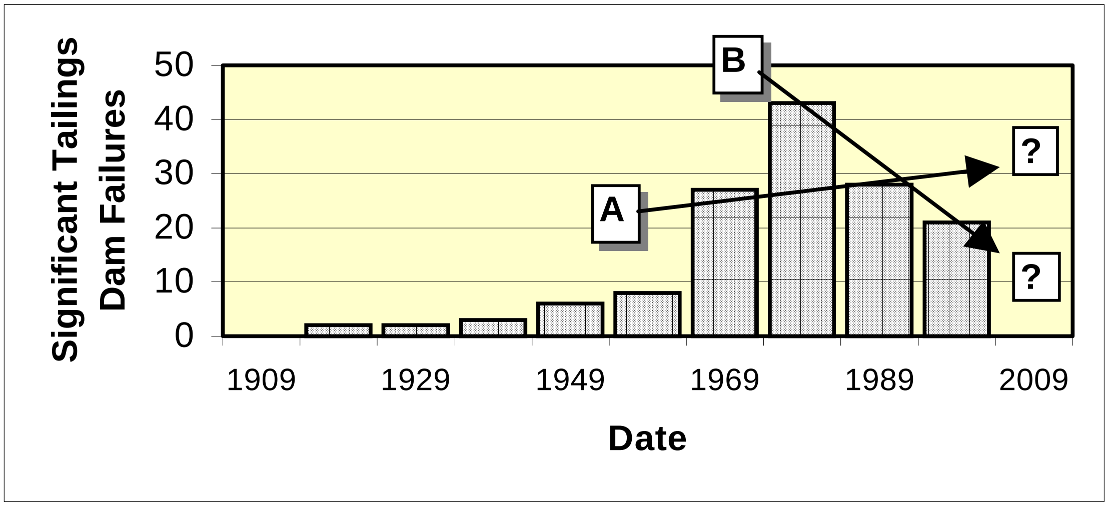


Figure 3. Frequency of significant tailings impoundment failures (USCOLD, 1994; UNEP, 1996 and authors' files) (adapted from Davies, 2001).

It is estimated that there are in the order of 3500 active tailings impoundments worldwide (Davies, 2001). Major failures occur at a frequency of less than 2 to 5 per year (i.e. about 0.1%), and minor failures at a frequency of about 35 per year (i.e. 1%). While low, these figures are still unacceptably high. Peck (1980) quoted reviews of the history of conventional (water storage) earth dam failures that concluded that the probability of catastrophic failure of a conventional earth dam during any one year is about one chance in 10,000 (i.e. 0.01%). The authors contend that, with the increasing emphasis on proper stewardship practices for tailings facilities, and industry-wide implementation of these practices, the favorable downward trend suggested on Figure 3 could continue. Ultimately, the objective must be to reduce the frequency of tailings dam failures (normalized to the number of tailings dams in existence) to a level no higher than that of conventional dam failures. This is an ambitious goal given that tailings dams must last for hundreds of years, while conventional dams have a shorter design life. However, the mining industry by its very nature has always been ambitious, and is undertaking initiatives to bring this ambition to fruition, as described in Section 5.6.

4.2 *What are the tailings dam failures telling us?*

The list of trends from the database, in terms of technical causes, has been in some form by many others (e.g., USCOLD, 1994). Reviewers of the case histories seldom point out the two most important conclusions, which are:

- There have been *no unexplained failure events*. If one becomes a student of tailings dam failure case histories, and all owners, designers and regulators should indeed do just that, a single conclusion arises. Every failure was entirely predictable in hindsight. As summarized by Davies et al. (2000), there are no unknown loading causes, no mysterious soil mechanics, no "acts of God", no "substantially different material behaviour" and definitely no acceptable failures. In all of the cases over the past thirty years, the necessary knowledge existed to prevent the failure at both the design and operating stage, but that knowledge was not used. This conclusion provides an optimistic view in that it implies that there are no "unpreventable" failures.
- Tailings dam failures often occur where one or more aspects of both design and construction/operation are deficient. Many failures, such as Merriespruit (Wagener et al., 1997), occurred as a result of operating practices that were incompatible with design requirements, or vice versa. This is not to say that a poor design can be saved by exemplary operating practices, nor that a good design can withstand poor operating practices. It merely indicates that the chances for failure are magnified when poor design is combined with poor operating practice.

- Too often the seeds of failure are sown at the very outset of a project, for example inadequate geochemical characterization of the tailings, and inadequate baseline hydrology/hydrogeology studies, resulting in a tailings facility design that does not protect groundwater quality, or a design that results in a long term ARD problem. Inadequate baseline studies commonly result in an "environmental" failure of the tailings facility. Inadequate geotechnical site investigations may lead to a tailings dam design incompatible with the foundation on which that dam is to be constructed. When bad decisions are made in the pre-feasibility or feasibility stages of a project, often due to pressures to minimize up-front costs to make a proposed project financially viable, adverse consequences almost always result. Realistic closure, care and maintenance costs must be considered at the very outset of a mining project.

4.3 *Environmental tailings facility failures*

One of the unique aspects of tailings facilities is that, even if the containment dam remains very stable, the facility can still undergo a failure from the environmental perspective. For example, a tailings facility can generate significant dusting problems impacting air quality. Another example is impacts on groundwater quality due to seepage from a tailings impoundment. These types of incidents, while not receiving the same degree of media attention as dramatic dam collapses, nonetheless constitute a failure, defined by Webster's dictionary as "a lack of success". UNEP (1996) provides a survey of tailings dam incidents, many of which involve groundwater quality impacts due to seepage from a tailings impoundment. The key lesson from these types of failures is that understanding of the geochemistry of the tailings, the tailings pond water, and the hydrology/hydrogeology of the site, is essential, and must be taken into account in the design, construction, operation, and closure of any tailings facility. As discussed above, environmental failures are often the result of inadequate baseline work when a project is being envisioned, and bad decisions being made on the basis of inadequate baseline work. It is far more effective, and inexpensive, to account for these factors at the onset of a tailings facility design than it is to account for them in subsequent remedial measures after a problem has developed.

5 RECENT INITIATIVES AND TRENDS – MANAGEMENT ASPECTS

5.1 *Mining Association of Canada*

The Mining Association of Canada (MAC), has recently published a document entitled "A Guide to the Management of Tailings Facilities" (MAC, 1998). This document, reviewed by industry and consultants, provides a framework of management principles, policies, and objectives, and checklists for implementing the framework through the life cycle of a tailings facility. The document is available on line at www.mining.ca, in English, French, and Spanish. It is general in nature, but this is appropriate in that the document recognizes the need for individual mining companies and mining operations to establish their own specific programs that meet their own specific needs. The objective of the guide is to "help the industry develop effective self-regulation, demonstrate due diligence, complement government regulations, practice continuous improvement, and protect the environment and the public" (MAC, 1998).

The checklists provided in the MAC guide identify six key elements for ensuring the effective implementation of the management framework:

- Management Action – from the management framework
- Responsibility – person responsible and accountable for delivery of a management action
- Performance Measure – indicator of progress toward a target or objective
- Schedule – time frame for completion of significant milestones of a particular management action
- Technical Considerations – relevant technical aspects requiring consideration
- Other References – additional technical, managerial and regulatory considerations related to the management action.

The MAC guidelines emphasize the need to “close the loop” in the management process, which includes confirming that management actions have been implemented, and which seeks to continually improve the management framework. The industry recognition of the need for this type of document demonstrates its recognition that a well-managed tailings facility is a safe tailings facility.

At present, MAC is preparing a follow up document to serve as a guideline in the preparation of Operations, Maintenance, and Surveillance (OMS) manuals for tailings dams. This represents the logical extension of the work carried out in development of the guidelines for tailings management. It is expected that this document too will be available on line at the MAC website given above.

5.2 *Canadian Dam Association*

The Canadian Dam Association (CDA) recently updated its dam safety guidelines (CDA, 1999). The update focussed in large part on incorporating elements specific to the safety of tailings dams. There are recommendations regarding the following issues that are very relevant to tailings dam stewardship:

- Responsibility for dam safety
- Scope and frequency of dam safety reviews, which includes a review of operations and maintenance, and dam surveillance program
- Operation, maintenance and surveillance, including need for an Operations Manual
- Emergency preparedness, including elements of an emergency preparedness plan (EPP)

These guidelines suggest that conventional earthfill dams and tailings dams share many of the same design criteria (for example, factor of safety against sliding failure). However, given that tailings dams must last in perpetuity, the tailings dam designer must recognize that they are designing for a period for which there is no design precedent. As such, long term mechanisms, such as weathering of rockfill or long term geochemical changes affecting filter performance, while not well understood at present, need to be considered. This presents those designing for closure with quandary of needing to know what is, at present, unknowable. The question must be asked “is a factor of safety of 1.5 adequate for this particular tailings dam?” Geotechnical design criteria for tailings dams have been “borrowed” from standards developed for conventional earthfill dams. However, tailings dams are not conventional dams, and design criteria for tailings dams must be considered, on a case by case basis, in that context.

5.3 *International Committee on Large Dams and Related Organizations*

The International Committee on Large Dams (ICOLD), and related organizations, have published numerous materials with regards to tailings dams. Bulletin 74 (ICOLD, 1989) presents guidelines for tailings dam safety. Bulletin 104 (ICOLD, 1996) specifically addresses monitoring of tailings dams. Other ICOLD publications pertaining to tailings dams are as follows:

Bulletin 97 (1994). Tailings Dams – Design of Drainage – Review and Recommendations.
Bulletin 98 (1998) Tailings Dams and Seismicity – Review and Recommendations
Bulletin 101 (1995) Tailings Dams – Transport, Placement and Decantation.
Bulletin 103 (1996). Tailings Dams and Environment. Review and Recommendations
Bulletin 106 (1996) A guide to Tailings Dams and Impoundments – Design, Construction, Use and Rehabilitation

The United States Committee on Large Dams (USCOLD) published a compendium of tailings dam incidents (USCOLD, 1994). This was probably the first attempt to catalogue and assess <u>published</u> information on tailings dam incidents. The document categorizes the various incidents in terms of technical causation, but there is no discussion of the extent to which inadequate stewardship played a role in the various incidents. The value of this document is that it discusses failure modes for different dam types, which is of benefit in developing requirements for a dam safety program, particularly dam surveillance. UNEP (1996) provides another survey of environmental and safety incidents for tailings dams.

ICOLD’s most recent publication pertaining to tailings dams is entitled “Tailings Dams - Risk of Dangerous Occurrences” (ICOLD, 2001). This document represents a continuance of the 1994 USCOLD effort in compiling a database of tailings dam incidents, and focuses on the lessons learned from these experiences. ICOLD reaches essentially the same conclusion as the authors: the expertise to design, construct, and operate tailings facilities in a safe manner exists. What is lacking is consistent application of this expertise to an appropriate standard of care.

5.4 *International Finance Corporation and International Standards*

There is increasing reference to application of “international standards” to the stewardship of tailings facilities, but no concrete definition as to what these “international standards” are. The demand for achieving “international standards” is being increasingly driven by financial lending institutions as a condition for approval of project financing. Bulletins pertaining to tailings dams published by the International Commission on Large Dams (ICOLD, see Section 5.3) are primarily guidelines and are relatively general in nature, but are often considered to represent “international standards”. Increasingly, “international standards” are interpreted to mean policies outlined by financing bodies, such as the International Finance Corporation (IFC), a branch of the World Bank. One of the key policies of the IFC (IFC Operational Policy 4.37, December 1998, available from www.ifc.org/enviro) requires that an Independent Review Panel (IRP) be established by the project proponent. Members of the IRP are to have expertise in the various technical fields relevant to the dam safety aspects of the third party review are as discussed in Section 5.6.4

5.5 *United Nations Environment Programme/International Council on Metals and the Environment*

The United Nations Environment Programme, Industry and Environment (UNEP), and the International Council on Metals and the Environment (ICME) have been active in recent years in sponsorship of seminars, and publication of case studies (UNEP-ICME, 1997 & 1998), related to tailings management. Many of the topics covered directly address stewardship issues. Mining companies provided most of the contributions to these publications, thereby making these forums an excellent means for dissemination of knowledge and experience to the international mining community. Key topics covered that relate to stewardship of tailings dams include:

- Corporate policies and procedures regarding stewardship of tailings facilities
- Evolving regulatory climates and trends
- Definitions of roles and responsibilities
- Application of risk assessment techniques
- Environmental management systems
- Emergency preparedness and response
- Education and training

Blight (1997), in the 1997 workshop sponsored by UNEP-ICME, and Wagener et al (1998), provide an in-depth discussion of the 1994 failure of the Merriespruit tailings dam in South Africa, in which 17 people lost their lives. Technical issues aside, these discussions are extremely valuable, and rare in the documentation of tailings dam failures, in that they explore how the inadequacies in the management aspects of the stewardship of the tailings dam allowed the technical factors that caused the failure to develop. As discussed previously, technical factors underlying tailings dam failures are well understood, and have been for many years. The technical causation of each new failure tends only to reinforce already well known principles. It is inadequate stewardship that permits such factors to manifest themselves in failures. All too often, published case histories on tailings dam failures focus solely on technical issues, without addressing the contribution of inadequate stewardship of the facilities to the failures. This is in large part due to legal entanglements that are one of the many inevitable consequences of failures.

The authors are aware of numerous examples where inadequate stewardship practices were the principal factor precipitating a chain of events leading to failure of tailings dams. The authors contend that such a link likely exists for most if not all tailings dam incidents, and this is why adequate stewardship of tailings facilities is so critical to their safety. Even the best-designed facility is susceptible to failure if not managed properly. Conversely, even a facility whose design is flawed can be operated successfully with good stewardship practice. Good stewardship, in the form of an ongoing dam safety evaluation program, should in fact allow a mining operation to detect any such design flaws and correct them in advance of any serious incident occurring.

Morgenstern (1998), in the 1998 UNEP-ICME workshop, succinctly summarized the challenges confronting the mining industry in stewardship of its tailings facilities, as follows:

> *"The standard of care associated with mine waste retention structures is too low."*
>
> *"A well-intentioned corporation employing apparently well-qualified consultants is not adequate insurance against serious incidents."*
>
> *"The standard of care associated with mine waste retention structures should move towards those of water-retaining structures."*

The following section outlines initiatives being undertaken by mining companies to meet these challenges.

5.6 *Initiatives by Mining Companies*

5.6.1 *General*

The most encouraging trend in terms of tailings dams stewardship is that it is the mining industry in general, and individual mining companies in particular, that are leading the way in improving state of practice and, equally as important, in sharing and publishing information within the industry. The following sections discuss some representative examples of proactive stewardship policies and practices being followed by mining companies.

5.6.2 *Corporate policies and management issues*

Several major Canadian-based mining companies have established corporate policies and procedures to ensure that all personnel involved in stewardship of tailings facilities, from the corporate level to the operators, clearly understand their roles and responsibilities (e.g., Siwik, 1997). Such an understanding, and enforcement (performance measurement) of those roles and responsibilities is vitally important. The authors have reviewed many tailings disposal facilities where there was no such understanding, and no "ownership" of key stewardship functions. A number of companies have also established policies with respect to degrees of training and competency required for the various roles involved in tailings facility stewardship (e.g. Siwik, 1997, Brehaut, 1997 and Maltby, 1997). This is also extremely important, especially for tailings dam operators, because they have the most frequent exposure to the facility, and usually are responsible for dam surveillance. It is essential that these personnel understand what to look for and why, what constitutes unfavorable conditions, and what to do about such conditions when detected.

Some companies have also established formalized dam safety programs (e.g., Coffin, 1998). Some of these programs include classification of each dam in terms of the consequences of a potential failure, which facilitates the dam safety review process and corporate prioritization of corrective measures, if required. Some of these programs include a detailed inspection and review of their tailings facilities by specialists (e.g. Coffin, 1998). Still others require that Operations Manuals be maintained for their tailings facilities (e.g. Maltby, 1997). In the province of British Columbia, in fact, Operations Manuals and annual inspections/reviews by specialists are a regulatory requirement.

5.6.3 *Auditing of tailings facilities*

Brehaut (1997) describes how, in an internal evaluation of its management systems, Placer Dome recognized that its tailings management systems were a priority for enhancement, and that tailings management was an issue that was to receive attention at a corporate level. Placer then embarked on development of guidelines to cover the design, construction, operating and closure phases of tailings management systems. Placer also determined that the application of risk assessment techniques was an essential next step in the review and enhancement of its tailings dam stewardship policies and procedures.

However, no sooner had this process been initiated than the Marcopper incident occurred at a property for which Placer Dome exercised a degree of management control in the Philippines, involving release of about 2 million tons of tailings into a local river system. As is widely known within the industry, but not appreciated without, Placer Dome's response to the incident was exemplary, and Brehaut (1997) indicated that the total cost to Placer Dome was estimated to be $43 million after insurance and tax recovery. The total cost to present far exceeds that value. Spurred on by the Marcopper incident, Placer Dome quickly initiated formal risk assessments of the tailings facilities at all of its operations. In many instances, these risk assessments were carried out, and/or facilitated by, geotechnical consultants who were not the engineers of record for the various facilities audited. The findings of these risk assessments (Brehaut, 1997) were that any design deficiencies identified were of minor significance, and the greatest weakness was related to management aspects of the stewardship of the facilities.

Many other mining companies have implemented similar risk assessment programs for many of their tailings facilities.

5.6.4 *Review boards*

Syncrude, Kennecott Utah Copper, and Inco, and numerous other mining companies, retain a board of eminent geotechnical consultants to provide independent review and advice in terms of the design, operation, and management of their respective tailings facilities. Such review boards are independent of the design engineers, be these consulting firms or geotechnical personnel the mining company has on staff. Review boards are now considered to be the state of dam stewardship practice for owners of major water dams. Dunne (1997) describes how Kennecott Utah Copper retained a geotechnical review board as a means of providing cost-effective quality assurance and risk management for the design of a major expansion of a 95 year old tailings impoundment near Salt Lake City.

Inco has a geotechnical review board for its Copper Cliff tailings facilities in Sudbury, Ontario. This tailings facility has been in use since the 1930's, and will not reach capacity until about 2030 (McCann, 1998). The review board represents a means of Inco applying its "fail-safe" review process to the design, construction, operation, and management of this large, historic tailings facility.

McKenna (1998) describes how Syncrude Canada Ltd., a large oilsands company in northern Alberta, has benefited from its geotechnical review board over the last 25 years, summarizing these benefits as follows:

- The board provides expert assistance in terms of assessing and managing risk.
- It ensures that all of the bases are covered (i.e. posing the question "has anything been missed?").
- Review board members bring to Syncrude a vast amount of varied practical experience and expertise.
- The board provides reassurance to senior management that an acceptable balance between risk-taking and conservatism is maintained in an operation where failure consequences are extreme.
- Independent review by pre-eminent specialists gains the trust of regulators and the public by providing an unbiased viewpoint, and facilitates the regulatory processes.
- Design engineers benefit through in-depth review of their work by pre-eminent specialists.

Another very important benefit afforded by a geotechnical review board is the continuity it provides. For example, over the 25-year period during which Syncrude has maintained a review board, there has likely been considerable turnover in staff and consultants. However, most of the current members of Syncrude's review board have been on the board, more or less continuously, since the board was first struck in 1972.

In summary, a review board can provide an objective view as to the potential, consequences, and cost of a potential failure, and help the owner ensure that decisions on design alternatives are not based solely on minimizing capital and operating costs. A review board provides the "*adequate insurance against serious incidents*" considered lacking by Morgenstern (1998) by "*a well-intentioned corporation employing apparently well-qualified consultants*". The IFC has recognized the benefits of a review board by stating the requirement for such a board in its operational policies for dam safety discussed earlier.

5.6.5 *Information database*

McCann (1998) describes systems that Inco has implemented to develop an information matrix to maintain records, in an easily retrievable manner, pertaining to the design, construction, operation and monitoring of its Copper Cliff tailings facilities, in use since the 1930's. For such a facility, given the inevitable turnover of operations personnel, management personnel, and design consultants, a good database is essential to maintaining continuity.

The authors cannot overemphasize the importance of this point, because they are aware of at least two recent tailings dam incidents that can be attributed in large part to the lack of such an accessible historical database, and/or inadequate appreciation of that database. Davies et al. (1998), discuss the static liquefaction failure of a portion of the Sullivan Mine active Iron Tailings Dyke, without off-site impact. A similar failure had occurred in 1948 and during that earlier failure, tailings flowed into the nearby town of Marysville. Museum records show the general public support for the mine and sympathy to the clean-up efforts. Had the 1991 incident progressed off-site, it is without doubt that the community response would have been dramatically less sympathetic and forgiving than was the case 50 years before.

The authors are aware of another tailings impoundment, in operation for over fifty years, which underwent a partial dam wall failure primarily as a result of key historical information not being readily available, not being adequately documented, and not being taken into account in design. That key historical information included no fewer than 5 previous similar dam wall failures. Good record keeping, and maintaining those records in good and easily accessible order, and appreciating the site-specific lessons provided by past experience, is an important aspect of stewardship of tailings facilities.

From collectively carrying out more than 30 risk assessments of tailings management facilities worldwide, the authors have reviewed the entire available "tailings library" at many mines. It is almost a certainty that any operation over 10 years of age will demonstrate "tailings database amnesia" and will repeat costly studies, ignore essential design criteria or unknowingly reinvent a tailings management plan without appreciation of the "forgotten" earlier information. Even large "incidents" are forgotten in many cases and the triggers to such events are allowed to re-establish due to lack of appreciation of a facility's history. Maintaining the same consulting organization does not seem to stem the onset of tailings database amnesia unless the mine itself is an active partner in tailings stewardship. The authors' review work also shows that tailings facilities that have had "incidents" in their past are often remarkably well-placed candidates to have them occur in the future.

5.6.6 *From audits to operations manuals to implementation*

On August 29, 1996, a portion of an upstream-constructed tailings dam collapsed at the Porco lead-zinc mine in Bolivia, with a resultant release of 400,000 tonnes of tailings. Following this incident, the owner initiated dam safety and environmental audits of its tailings facilities (active and inactive) in Bolivia and Argentina. This was the first step in a process that saw the owner, within a year, implement a formal stewardship program for its tailings facilities, including training, monitoring and surveillance programs, and Operations Manuals for each operation. An environmental management system (EMS) was developed and implemented concurrently. Training seminars on environmental monitoring, tailings management and surveillance of tailings facilities were undertaken, developed to address the specific attributes of each of the operations. These training seminars, presented on site to mine management and operators, were also used as a forum to begin the development of Operations Manuals, and provided a means to involve both operations and management personnel in the development of these manuals. Equally as important, these sessions were used to gain their buy-in to the process and the end product. There was also corporate level participation in the development of these manuals, and in the training seminars.

The authors believe that the interactive development (not just the end product) of a comprehensive Operations Manual for a tailings facility can be the single most important and pro-active measure in formalizing and implementing good stewardship practices of tailings facilities. Operations Manuals should embrace the following key elements of a comprehensive tailings dam stewardship program:

- Project administration, and responsibilities for facility operation, safety and review (including corporate level roles and responsibilities).
- Design overview and key design criteria.
- Tailings deposition and water management plans.
- Planning requirements (reviews, construction, operation, training).
- Training and competency requirements.

- Operating systems and procedures.
- Dam surveillance, including checklists, signs of unfavorable performance, and responses to unusual readings/events/observations.
- Reporting and documentation requirements.
- Emergency action and response plans.
- Construction and QA/QC requirements.
- Standard formats for monthly status reports for tailings facilities, and for performance reviews.
- Reference reports and documents.

The benefits of having an Operations Manual in place are as follows:

1. It provides a concise, practical document that can be used by site operating personnel for operation and surveillance of the tailings facilities.
2. It serves as a useful training document for new personnel involved in tailings management and operations.
3. Its existence provides reassurance to senior level management, and to regulators, that formalized practices are in place for the safe operation of the facility.
4. It demonstrates due diligence on the part of the owner.
5. It provides an important means of defense against tailings dam amnesia.

Reliance on the preparation of an Operations Manual by a consultant only should be discouraged, as this does not foster an intrinsic understanding of each part of the manual by operations personnel. Further, it is essential that an Operations Manual takes into account the perspective, knowledge and experience of operations personnel.

5.7 *The Role of Tailings Facility Design Consultants*

5.7.1 *General*

Tailings facility design consultants have an essential role to play in promoting good stewardship of tailings facilities, besides the obvious technical role of providing safe, cost-effective, practical and enduring designs. The following sections discuss a number of ways consultants have, are, and should be contributing to this effort.

5.7.2 *Publications and participation in conferences*

Tailings consultants often (and should) work on a variety of projects, in many countries and for many clients. By so doing, they amass a wide array of varied experience from which the mining industry and other consultants can and should be made to benefit. Conferences, such as the annual Tailings and Mine Waste series in Fort Collins as one example, provide a forum for interchange of ideas and sharing of experiences. More emphasis, however, needs to be placed on stewardship issues as opposed to the purely technical topics that typically dominate such conferences.

Consulting engineers specializing in tailings dams have also contributed through publication of entire books on the subject. The first such book with widespread distribution was written by Steve Vick, entitled “Planning, Design, and Analysis of Tailings Dams” (Vick, 1983). It is an excellent treatise recommended for all persons responsible for some aspect of tailings management. More recently, Dr. Maciej Szymanski published a book entitled “Evaluation of Safety of Tailings Dams” (Szymanski, 1999). This book provides a detailed discussion of elements of a comprehensive dam safety program specifically tailored to the unique requirements of tailings dams. Issues related to good stewardship practices are discussed throughout.

5.7.3 *The design product*

The design product provided by tailings engineers to the owner is, all too often, rich in discussion of the finer points of soil mechanics and hydrogeology, but poor in terms of detailed guidance for pragmatic operation and surveillance. The condition of a tailings facility is governed by how it is operated and constructed, not necessarily by how it was designed. Likewise, its safety is better judged based on surveillance than design analyses in the appendix of some design report. The design report must therefore include operational and surveillance requirements. Ideally, an Operations Manual, or at least most elements of one, should be provided with the design, otherwise the design is not complete. The designer should also outline the requirements of a dam safety program for the tailings facility, for both the operational and the closure phases.

5.7.4 *Risk analysis*

Consultants and mining companies are increasingly applying techniques that can be broadly categorized as "risk analysis" to various facets of tailings management, most notably in reviews of existing facilities. Risk-based analysis and decision making also appear to be gaining popularity as a way of communicating project information to regulators and stakeholders in proposed new projects. Mining companies are also applying such techniques in the stewardship of their tailings facilities. A risk analysis, by the authors' definition, provides answers to the following questions:

1. What can go wrong?
2. How likely is it that it will happen?
3. If it does happen, what are the consequences?
4. What can/should be done to reduce the likelihood and/or consequences of this potential occurrence?

There are many interpretations as to the definition of risk, and as to what a risk analysis is, as to what risk assessment is, and what such analyses and assessments achieve. Clear and consistent definition, interpretation and use of risk management terms does not yet exist. Definitions and interpretations presented by the Dam Safety Interest Group (DSIG) (1999), and the draft ICOLD bulletin on risk assessment (ICOLD, 2000) are steps to standardization of risk management terms.

The authors have made frequent use of forms of the qualitative failure modes and effects analysis (FMEA) in workshop settings that include mine management and operating personnel. FMEA, and most other qualitative risk assessment methods, are nothing more than organized judgement, common sense with a fancy name. Being a qualitative technique they are inevitably subjective, yet remain a useful risk management screening tool. Much more sophisticated, quantitative risk analysis techniques are also available. Risk analysis techniques can be used to audit any number of technical and managerial aspects of tailings dam stewardship.

As an example, the FMEA technique, carried out in a workshop setting, is particularly effective in scoping out requirements for dam surveillance, and ties in well to the correct application of the observational approach (see Figure 4), the rigorous application of which is so fundamental to tailings dam design and safety. The FMEA process captures the key elements of comprehensive dam surveillance, including:

- Identification of potential failure modes
- Identification of warning signs for failure modes
- Consideration of how quickly failure could occur, and how potential problems can be detected well in advance of their developing into incidents
- Consideration of the significance of temporal trends as opposed to single measurements/observations
- Allows "green light" (safe) versus "yellow light" (caution) versus "red light" (stop) limits/criteria to be established

The workshop format, involving personnel responsible for dam surveillance, as well as management personnel, provides the following:

- Forum for interchange of ideas and concerns
- Technical, operational, environmental, and management input
- Transfer of essential knowledge from the designers to "front-line" personnel, and vice versa
- Development of a team approach to dam surveillance
- Buy-in from responsible parties

The FMEA process is illustrated schematically in Figure 5, and provides the following:

- A structured, repeatable, and documented process
- Assessment of current surveillance practices in terms of scope, frequency, reporting and interpretation, response to unusual conditions, and resources available versus resources required
- Identification of aspects requiring improvement
- Justification for allocation of resources to dam surveillance
- An action plan that evolves directly from the process

Special emphasis is placed on the subject of dam surveillance by the authors because, with the obvious exceptions of failures triggered by earthquakes or major storm events, many types of failure give some warning signs (Smith, 1972), making dam surveillance a critical aspect of proper stewardship. Assisting an owner develop a comprehensive dam surveillance program is a vitally important responsibility borne by the designer.

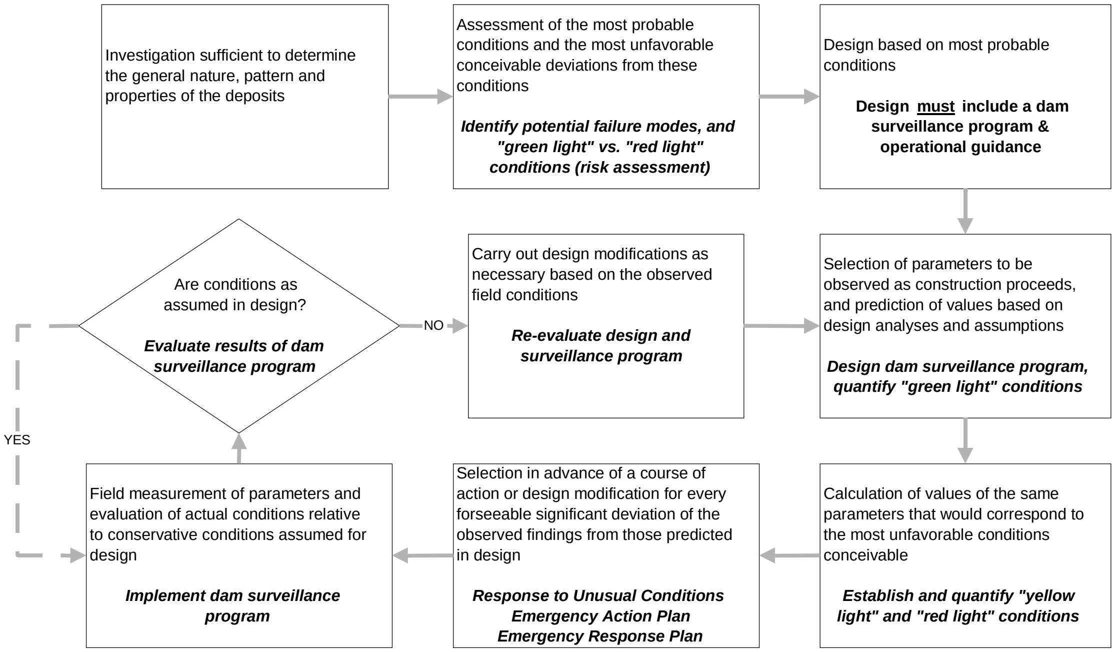


Figure 4. Risk analyses and the observational approach applied for dam surveillance

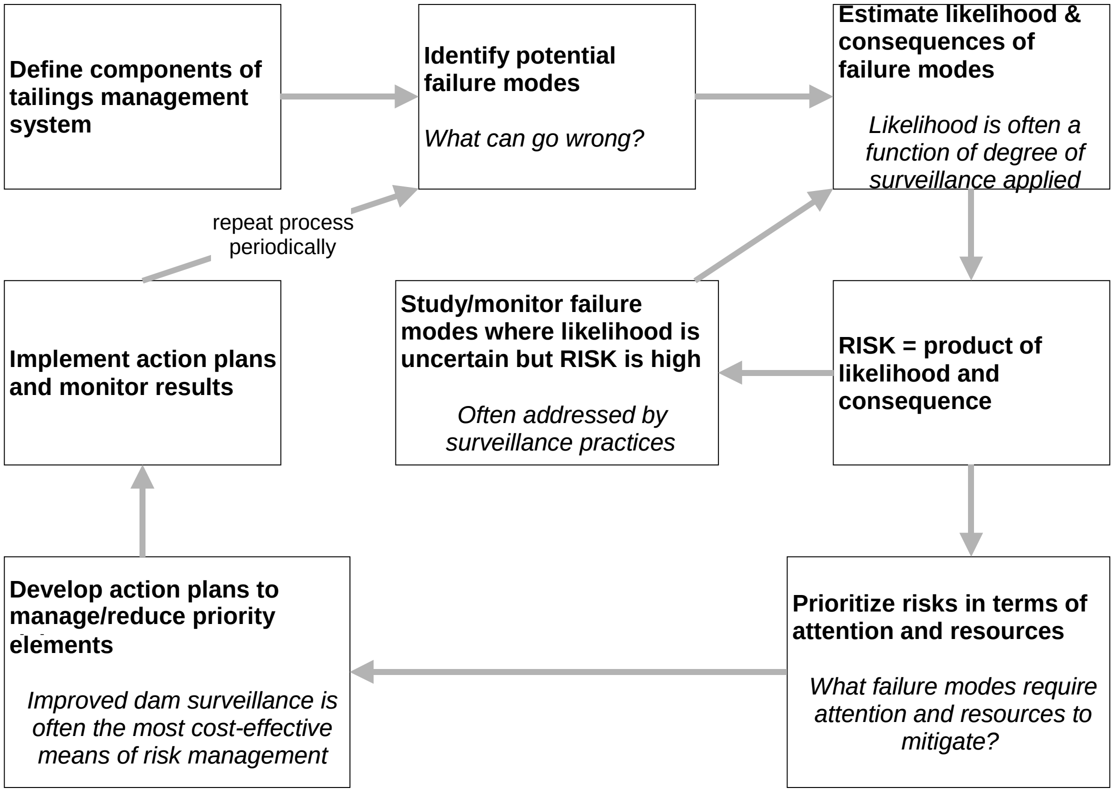


Figure 5. Risk analysis and assessment process

5.7.5 *Training seminars*

Consultants are increasingly being called upon to provide on-site training to operators, and this is a very welcome trend. This facilitates transfer of key knowledge from the design engineer to the operators, who represent the designer's "eyes and ears". Such seminars are as beneficial, if not more so, for the designer as the operators, providing the designer with a reality check on the constructability of the designs and the practicality of the operating requirements imposed by the designs. It is the authors' experience that designers can learn more of practical benefit to themselves and their client from a day on site with experienced operators than a week of reading technical papers. Tailings dam operators truly appreciate such seminars, which facilitates their buy-in, understanding, and commitment to good stewardship practices. These seminars help to build the designer-operator partnership that is such a critical element of stewardship of tailings facilities.

5.7.6 *Designer Expertise and Perspective*

As noted earlier, tailings dams and impoundments are unique structures in the engineering world. Commensurately, design consultants should have appropriate educational and practical experience directly applicable to tailings dam design. Moreover, a proven construction and operations history for the designer's projects is of extreme importance. There are a limited number of qualified designers and organizations (more than one designer in house). Owners should share information with one another as much as possible regarding design consultants. It is an unfortunate, but very real, fact that "all designers are not born equal". Independent peer reviews, or review boards, are means by which mining companies can protect themselves from questionable designs, and design consultants should proactively encourage their clients to adopt these protective measures, which, as discussed previously, are also very much to the design consultants benefit. The authors have noted a recent trend where regulators are requiring some mines to retain such a review board for large tailings facilities.

Designers themselves need to maintain an appropriate balance between the real world (i.e. case history experience, both good and bad) and theory (e.g. laboratory testing and visco-plasticity theory), with the real world always being the most important. Prior to the birth of tailings dam engineering as a formal discipline in the late 1960's, tailings dams were designed and constructed based almost entirely on experience (trial and error), without the benefit of soil mechanics theory. Today, the pendulum may have swung too far in the opposite direction, with many tailings dams being designed "in the laboratory" and in computer simulations. The authors have noted that regulators in many jurisdictions have become overly prescriptive in the types of analysis required for tailings dams, despite the fact that analyses that have predicted stable dams will not prevent instability if the design is deficient.

The engineering principles for constructing and operating stable tailings were understood in the 1970's, and have not changed significantly with the advent of advanced analytical and laboratory testing capabilities since that time. The man considered the founder of soil mechanics, Dr. Karl Terzaghi, is reputed to have said that *"nature has no contract with mathematics; she has even less of an obligation to laboratory test procedures and results"*. Terzaghi's colleague, Dr. Ralph Peck pointed out that theory can inhibit judgement if used without discrimination and without critical evaluation (Peck, 1980). Another of Terzaghi's colleagues, Dr. Arthur Casagrande, advocated that embankment dams be designed and constructed according to the "belt and suspenders" principle. The economic pressures inherent in the mining industry can lead to the temptation to include the belt but not the suspenders. This temptation is false economics, and must be resisted.

5.8 *Regulatory Trends*

5.8.1 *General*

Regulatory agencies typically do not "prescribe" stewardship practices to the industry, apart from some basic requirements (in some jurisdictions) like requiring a dam surveillance program, requiring annual reports, operations manuals, and so on. It is in terms of environmental issues (water quality, for example) that regulations are, necessarily, prescriptive. This is as it should be, because mining companies themselves, supported by their design consultants as appropriate, are best qualified to design stewardship programs appropriate to their particular facilities. An attempt by regulators to impose a uniform "code of stewardship" would be unsuccessful because each mining company, and each tailings facility, have their own unique requirements, resources, constraints, and site conditions. So much of stewardship relates to the corporate and mine-specific organizations and personnel, aspects that cannot be effectively regulated, but which require a high degree of self-regulation.

5.8.2 *Regulatory Trends in Developing Countries*

An interesting regulatory trend is that codes and standards with respect to tailings disposal are gradually becoming "harmonized" internationally. Many developing companies, Bolivia being but one example, have only recently enacted regulations covering tailings disposal. These regulations are largely modeled after World Bank guidelines and regulations in North American jurisdictions. Unfortunately, there appears to be a trend among developing countries to make their regulations technically prescriptive, with some (e.g. Peru) actually presenting a very elementary course in soil mechanics, describing methods of stability analysis and liquefaction potential screening methods. This is due in part to the comparative lack of skill and expertise (capacity) in tailings dam engineering on the part of the regulators. It is also due to their understandable desire to have tailings facilities in their respective countries conform to "international" (i.e. ICOLD) standards, which as discussed previously really do not exist in any tangible, readily-referenced form. Technically prescriptive regulations can provide a false sense of security to the regulators and, worse, the mining companies themselves. Many failure case histories likely involved facilities that were in conformance with all regulations, except the most important of all (the dam failed).

Reliance on regulations full of prescriptive design criteria that meet "international standards" and full of elementary soil mechanics principles do nothing to address actual operating practices and stewardship issues. As discussed previously, even the most robust design can fail if not stewarded properly. As regulations generally do not address stewardship issues, it is incumbent on the mining industry to take the lead and become effectively self-regulating in this regard. The mining industry, and its consultants, could be of great assistance to regulators and the public in developing countries by providing training and workshops for regulatory personnel responsible for tailings facilities, and by informing the public. This sort of capacity-building would be of great benefit to all of the industry's stakeholders. It is in the mining industry's best interest to achieve a condition of "co-regulation", whereby mining companies regulate themselves to a greater degree than do the regulatory agencies. This is also in the best interests of regulators, given their often scarce time and resources.

5.8.3 *Regulatory Trends in Developed Jurisdictions*

In more developed jurisdictions (for example, the authors' home jurisdiction of British Columbia), the regulators employ geotechnical engineers experienced in tailings management. Here, regulations are not prescriptive, neither in the technical nor the stewardship sense, because regulators have the expertise to assess the design of each tailings facility, and the manner in which it is operated, on a case by case basis. The B.C. regulations do require that an Operations Manual exist for each tailings facility, but the contents of those manuals are up to the owner, and are subject to the review and approval of the regulator. Similarly, a dam surveillance plan is also required (typically included in the Operations Manual). However, the details of tailings dam stewardship are left to the individual operations. An annual review report, prepared by a qualified geotechnical engineer, is also a regulatory requirement.

In B.C., the regulators have actually assisted the industry by publication of a document entitled "Tailings Dam Inspection Manual". This document is not a set of regulations, but rather is intended to assist regulatory and mine personnel in inspection of tailings dams. B.C. regulators are currently working with regulators in Peru to achieve a "knowledge transfer" to Peruvian regulators. This type of capacity-building between regulators in different jurisdictions is a welcome trend. The mining community is now international, and includes mining companies, its consultants, regulators, and the public. The more these four bodies can assist one another in facilitating good stewardship practices through capacity-building, the better off everyone will be.

Another example of regulators assisting industry is the "Best Practice Environmental Management in Mining" series published by the Environment Protection Agency (EPA) in Australia. One of these documents deals with the fundamentals of tailings containment (EPA, 1995), and another with dust control (EPA, 1998). These documents are very rudimentary, but serve to outline key principles to be incorporated into tailings management operations in Australia.

5.8.4 *Embracing more robust designs & new technologies*

Regulators in North America and overseas are showing an increasing acceptance of and, in many cases, preference for, more robust design approaches and tailings handling technologies. The authors have been involved in several proposed projects in recent years where the project proponent specified more robust and non-traditional tailings handling approaches largely out of a desire to facilitate the permitting process, even though an acceptable case could have been made for proper application of more traditional methods. Some of the recent trends in developing tailings management technologies are discussed below in Section 6.

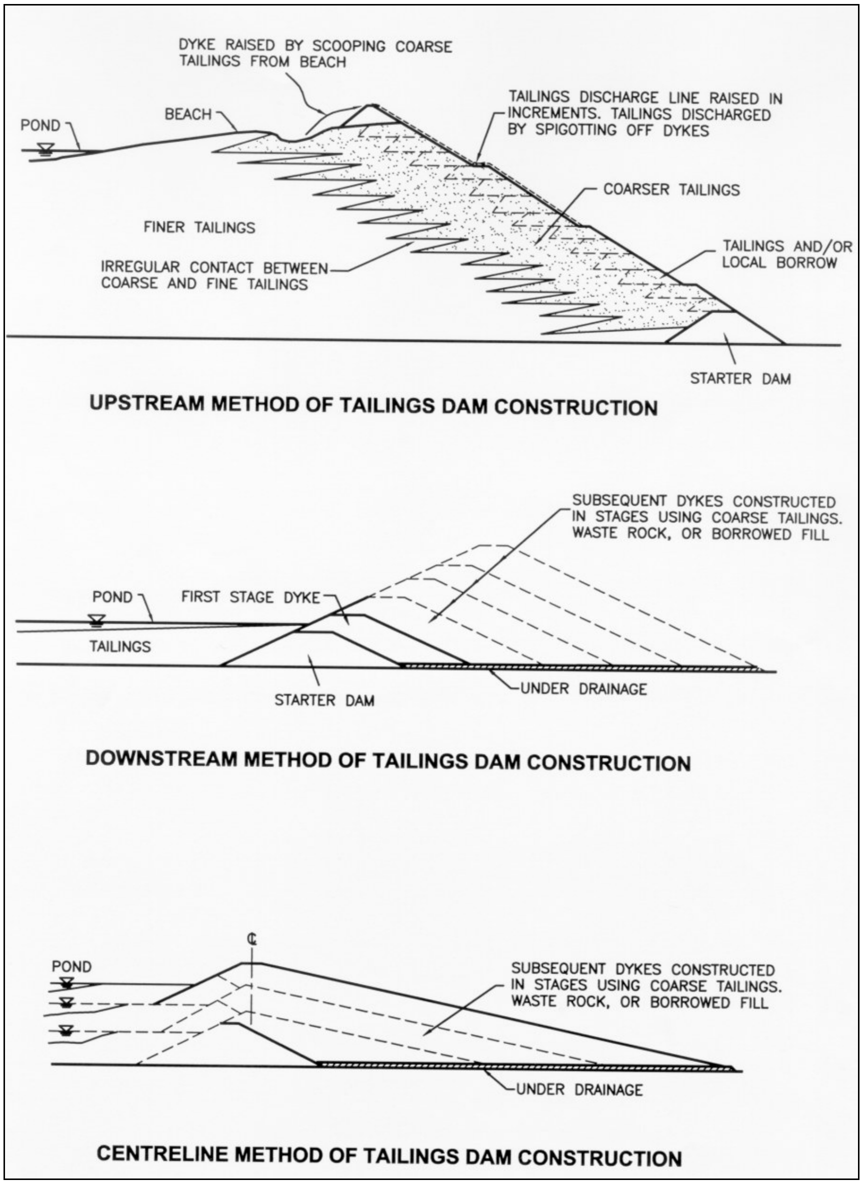
6 RECENT TRENDS – TAILINGS MANAGEMENT TECHNOLOGIES

6.1 *Improved Basic Management Practices*

A landmark paper on tailings dams, entitled Design and Construction of Tailings Dams, by Earle J. Klohn, was published in CIM Transactions, Vol. LXXV, 1972. Klohn won the EIC Leonard Medal for this paper and it has stood as an important work since that time. The following sections present an update of some of the improvements to basic tailings management practices that have been developed and implemented by the mining industry since then.

6.1.1 *Improved Upstream Construction*

The three basic tailings dam geometries are as shown in Figure 6. Centerline and downstream constructed tailings dams are generally considered to be more robust than upstream tailings dams. The failures have been the results of earthquakes, high saturation levels, steep slopes, poor water control in the pond, poor construction techniques incorporating fines in the dam shell, static liquefaction, and failures of embedded decant structures. Most failures have involved some combination of the above weaknesses. As a result, considerable attention has been given to improving traditional upstream dam construction to make the technique not only economical but also stable under both static and dynamic conditions.



UPSTREAM METHOD OF TAILINGS DAM CONSTRUCTION

DOWNSTREAM METHOD OF TAILINGS DAM CONSTRUCTION

CENTRELINE METHOD OF TAILINGS DAM CONSTRUCTION

Figure 6 Tailings dam geometry definitions

Based on the failure experiences as described above, safe, optimized designs have been developed for upstream constructed tailings dams. Some of the key design features that have been added, and are illustrated on Figure 7, include:

a) under-drainage, either as finger drains or blanket drains, to lower the phreatic level in the dam shell;
b) beaches compacted to some minimum width to provide a stable dam shell. Beaches are compacted by tracking with bulldozers, which are also used for pushing up berms for support of spigot lines;
c) Slopes designed to a lower angle than was used for many failed tailings dams. Slopes are generally set at 3 horizontal to 1 vertical or flatter, depending on the other measures incor-

porated into the designs. Steeper slopes, without an adequate drained and/or compacted beach, create the potential for spontaneous static liquefaction - a phenomenon not widely recognized in 1972 but one responsible for a number of major tailings dam failures.

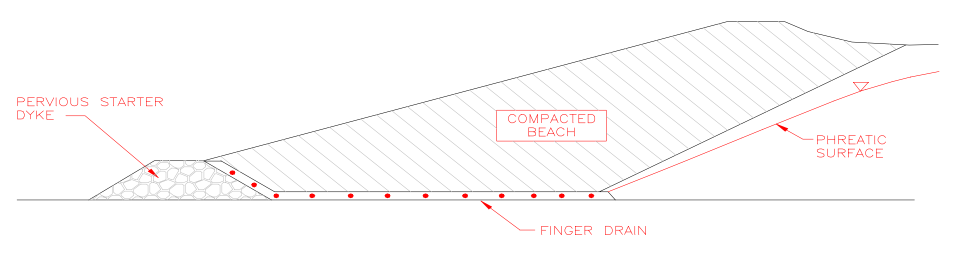


Figure 7. Typical section of improved upstream tailings dam design.

6.1.2 *Lined Tailings Impoundments*

With the advent of larger gold mining operations, and the almost universal use of sodium cyanide as an essential part of gold extraction, the need came about to develop impervious impoundments to contain cyanide solutions. Although cyanide is in most forms an unstable compound that naturally breaks down on exposure to air, it can be very persistent and migrate long distances in groundwater. As well as cyanided gold tailings, other types of tailings may also be considered potentially contaminating. For protection of aquifers, where tailings impoundments are not sited over impervious soils or bedrock and embankment cutoffs are not sufficient to reduce seepage, it is often necessary to design and construct a liner over the base of a tailings impoundment. Great progress has been made in liner design and construction practice.

Liners may be as simple as selective placement of impervious soil to cover outcrops of pervious bedrock or granular soils, or may need to be a composite liner system constructed over the entire impoundment. Where geomembrane liners are used, it is normal practice to incorporate a drainage layer above the geomembrane, to reduce the pressure head on the liner, and to minimize leakage through imperfections in the liner. Another benefit of such under-drainage is that a low pore pressure condition is achieved in the tailings, giving them a higher strength than would exist without such under-drainage. The drainage layer typically consists of at least 300 mm of granular material, with perforated pipes at intervals within the drainage layer. The pipes are laid to drain water extracted from the base of the tailings deposit and to discharge to a seepage recovery pond. Figure 8 shows two typical configurations of lined impoundments. Figure 8a shows a liner extending up the face of the embankment, requiring special detailing of drainage pipe penetrations through the liner. In Figure 8b, the liner extends beneath the embankment. In the latter case, care must be taken to design for lower foundation shear strength for the downstream slope of the embankment, as the liner may form a plane of weakness.

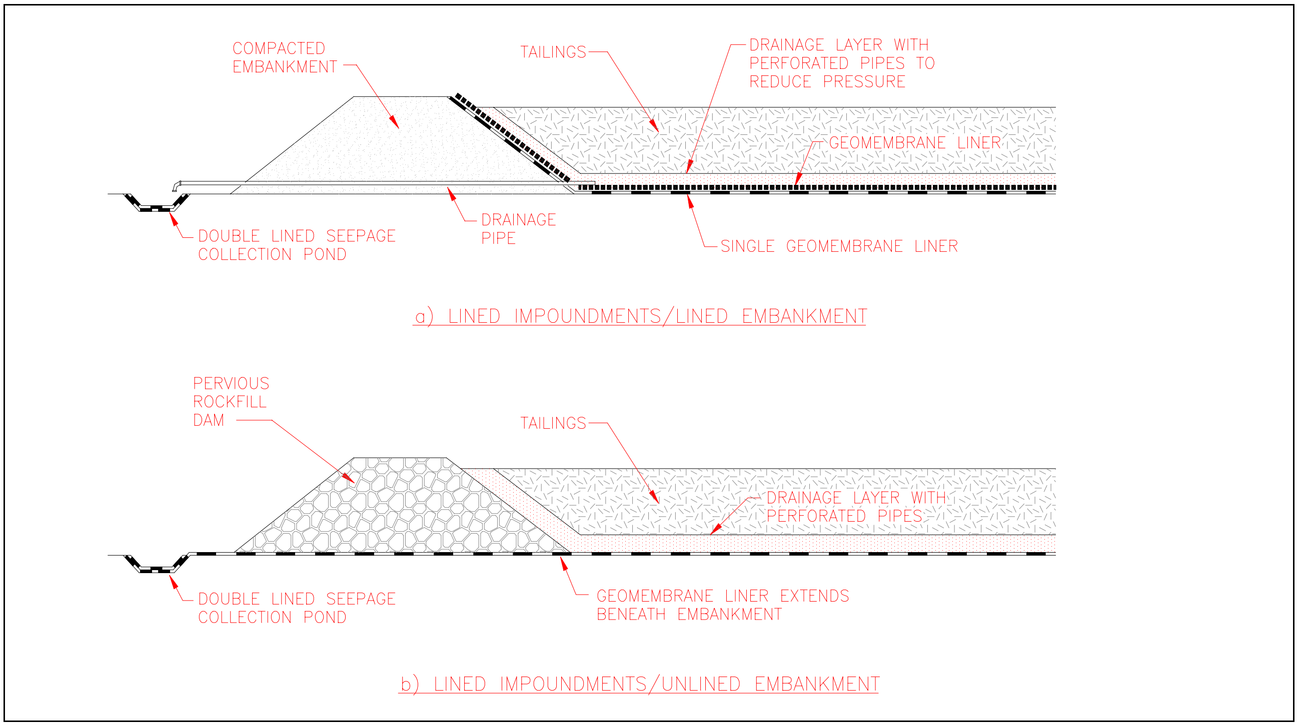


Figure 8: Conceptual sections of lined impoundments with underdrains

6.1.3 *Dewatering Technologies*

As shown on Figure 9, the basic segregating slurry is part of a continuum of water contents available to the tailings designer. Although tailings dewatering was previously practiced for other purposes in the mining process, until recently the only form of tailings for most tailings facilities was the conventional segregating, pumpable slurry with water contents of well over 100%.

There are several candidate scenarios where dewatered tailings systems would be of advantage to the mining operation. Dewatered tailings systems have less application for larger operations for which tailings ponds must serve dual roles as water storage reservoirs, particularly where water balances must be managed to store annual snowmelt runoff to provide water for year round operation.

a) "Dry" cake filtered tailings

Development of large capacity, vacuum and pressure belt filter technology has presented the opportunity for disposing tailings in a dewatered state, rather than as a conventional slurry. Davies and Rice (2001) describe the basic elements of filtered tailings management. Filtering can be carried out using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Pressure filtration can be carried out on a much wider spectrum of materials though vacuum belt filtration is probably the most logical for larger scale operations. Tailings can be dewatered to less than 20% moisture content for typical tailings of specific gravities near 2.7 (using soil mechanics convention, in which moisture content is defined as weight of water divided by the dry weight of solids), in a filter plant, an examples of which are shown on Figure 10. At these moisture contents, the material can be transported by conveyor or truck, and placed, spread and compacted to form an unsaturated, dense and stable tailings stack (often termed a "dry stack") requiring no dam for retention. While the technology is currently considerably more expensive per tonne of tailings stored than is the case for conventional slurry systems, and may be prohibitively expensive for very large tonnage applications, it has particular advantages in the following applications:

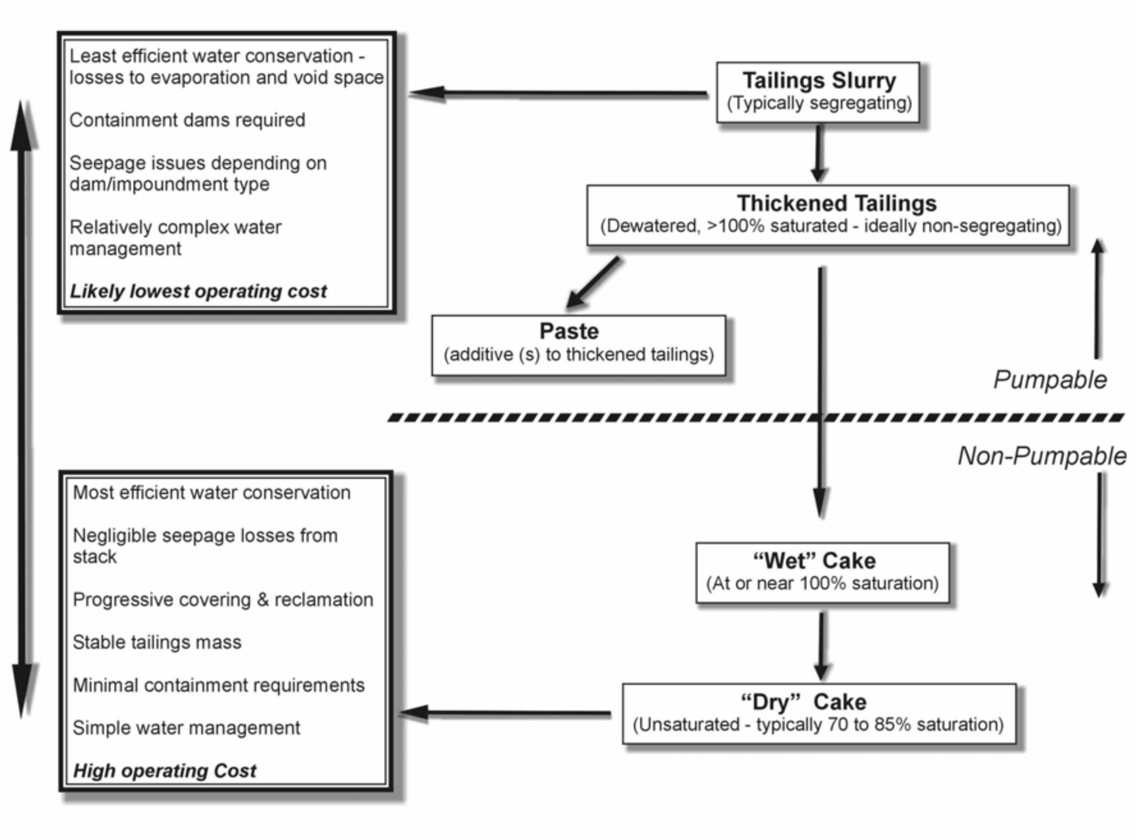


Figure 9. Classification of tailings by degree of dewatering

- In arid regions, where water conservation is an important issue. The prime example of such system is at the La Coipa silver/gold operation in the Atacama region of Chile. A daily tailings production of 18,000 t is dewatered by belt filters, conveyed to the tailings site and stacked with a radial, mobile conveyor system. The vacuum filter system was selected for this site because of the need to recover dissolved gold from solution, but is also advantageous for water conservation and also for stability of the tailings deposit in this high seismicity location; and
- In cold regions, where water handling is very difficult in winter. A dewatered tailings system, using truck transport, is in operation at Falconbridge's Raglan nickel operation in the arctic region of northern Quebec. The system is also intended to provide a solution for potential acid generation, as the tailings stack will become permanently frozen. A dry stack tailings system is also being planned for a new gold project in central Alaska.

Moreover, filtered tailings stacks have regulatory attraction, require a smaller footprint for tailings storage (much lower bulking factor), are easier to reclaim and close, and have much lower long-term liability in terms of structural integrity and potential environmental impact. Figure 11 shows a photograph of a large dry-stack tailings system.

Filtered tailings are not a panacea for the mining industry for its management of tailings materials. Purely economic considerations rarely indicate a preference for dry stacked tailings facilities over conventional slurry impoundments, the main reason being that closure costs are rarely factored into the equation when developing the comparative costs. However, under a growing number of site and regulatory conditions, filtered tailings offer a real alternative for tailings management that is consistent with the expectations of the mining industry, its regulators and the public in general.

b) Other dewatering technologies. It is critical before basing mining operations on new technologies to carry out adequate engineering studies to demonstrate feasibility. Several tailings disposal technologies have been introduced to the mining industry that, over the past 30 years, have not proven out to be as effective as hoped. While all have contained good ideas, they have often been wholly or partially unsuccessful, or have not found extensive application to date. Often, the development of new tailings technologies focus on solving a specific problem without determining potential impacts on the overall operation that may create new problems elsewhere in the system. Impacts on water supply and water chemistry are examples of potential problems that can be caused by switching to new tailings process technologies. Two developments will likely see renewed emphasis over the coming years.

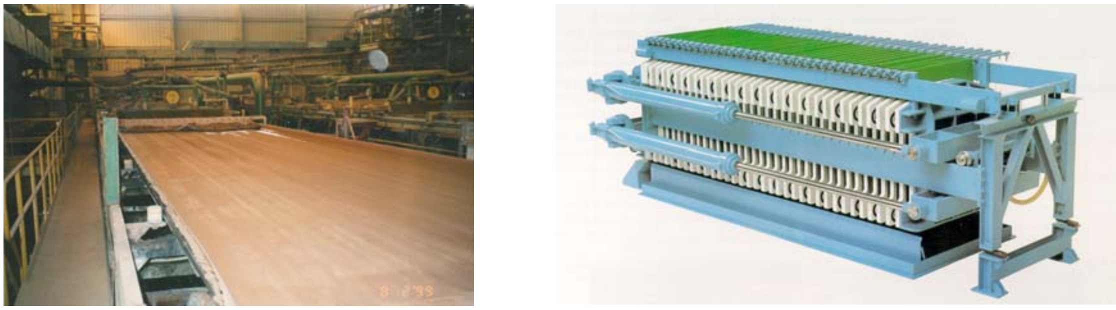


Figure 10 Examples of a filter plant

Figure 11 Example Dry-Stack Tailings Facility

- **Paste disposal.** The development of improved thickener technology has led to tremendous advances in paste tailings for underground backfill operations. Paste tailings are essentially the whole tailings stream, thickened to a dense slurry (previously only the coarse fraction of tailings was separated from tailings for use as backfill). Cement is added to the thickened tailings and the material is pumped underground to use as ground support in mined out stopes. Advocates of paste technology have promoted its use for surface tailings disposal, claiming that it can be placed in stable configurations with the cement providing adequate strength. Until recently, the technology had not yet been shown to be economically pragmatic at a large scale for surface application. Other such applications are in the planning stages, and operating experience with this approach will soon become available. Paste disposal shares many of the advantages of filtered tailings and can be economical when combined with the need for paste backfill underground.

- **Thickened disposal.** Thickened tailings are paste without the additives. Thickened disposal is a technique that has been proposed for over 25 years and has been implemented in a few operations, most notably and successfully in arid regions of Australia. The main premise of thickened disposal is that tailings may be thickened to a degree that they may be discharged from one or several discharge points to form a non-segregating tailings mass with little or no water pond. In the most classical connotation, thickened tailings are assumed to form a conical mass with the tailings surface sloping downwards from the centre of the cone. A thickened tailings system, if successful, should require lower retaining dykes, as storage is gained by raising the centre of the impoundment. It had been proposed that, at the start of operations, the tailings could be thickened to a lesser degree, when flatter slopes on the impoundment would suffice, then later thickened to a higher degree as it became necessary to raise the central point of the cone. In most instances where thickened tailings was implemented, thickening technology was not capable of producing a consistent non-segregating material, so fines would form a very flat slope and require additional dyking at the toe. As well, the predicted slopes used in the design and planning of the deposit were based on laboratory flume tests. The actual slopes were flatter than predicted, and it was not possible to steepen these slopes to avoid extensive land use impact. Therefore, the vision of low perimeter containment dykes which was a key advantrage of the concept is only a reality where real estate is unlimited. From the above experiences, the thickened disposal method did not become widely accepted and applied in Canada where the concept was initially developed by E.I. Robinsky (1979) for the Kidd Creek tailings facility near Timmins, Ontario. It has, however, been very successful in very arid regions, such as the key mining districts of Australia, one of these examples being shown in Figure 12. In recent years, high density thickening technology has been developed which make it useful to re-examine thickened disposal. The authors are aware of several major mining projects considering thickened tailings as an alternative management practice, but in most cases the advantages presented by the thickening process (i.e. water recovery, non-segregating tailings etc.) have been de-coupled from the deposit characteristics.

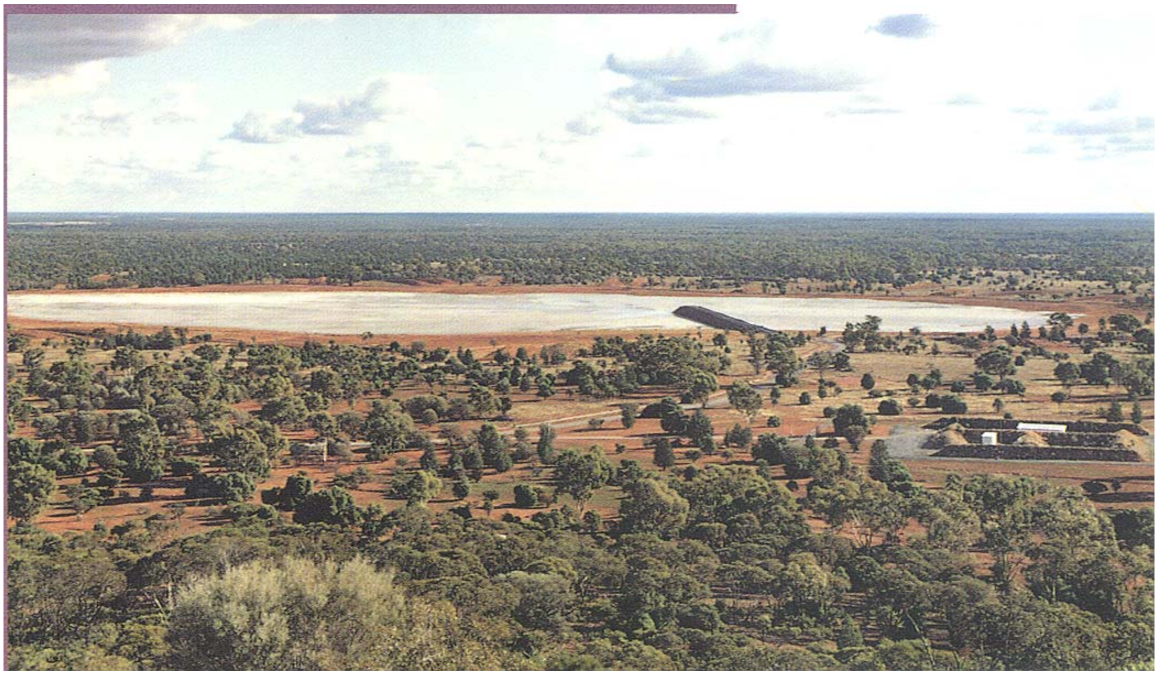


Figure 12 Example thickened tailings deposit - Australia

6.1.4 *Emerging initiatives and technologies*

Research into other means of handling tailings beyond those described above is ongoing on many fronts. The initiatives being researched have in common the objective of producing a more physically and/or geochemically stable tailings mass with reclamation factored into the design and construction planning. Two examples of current research initiatives are discussed below.

Wilson (2001) summarizes ongoing research into the co-disposal of tailings and waste rock for mines with ARD issues. This research is focused on disposing of waste rock and tailings as a single waste stream, instead of as two separate waste streams, one wet (tailings) and the other dry (waste rock). Sulphidic waste rock has high shear strength, but is highly pervious to water and atmospheric oxygen and so is highly susceptible to ARD. Tailings are much less pervious to water and atmospheric oxygen, but when deposited in conventional slurry impoundments have a very low shear strength, and are susceptible to liquefaction and subsequently catastrophic flowslide behavior. The fine-grained nature of tailings promotes water retention and saturation, which inhibits oxygen flux. By combining tailings and waste rock, the beneficial qualities of each type of waste (waste rock - high shear strength, tailings - low permeability) can be realized. The resulting single tailings stream would be more physically stable (higher shear strength) and would be more chemically stable (reduced oxygen flux and reduced ARD). Co-disposal of tailings and waste rock may have particularly promising potential for the construction of a low permeability cover for tailings ponds and waste rock dumps (Wilson, 2001).

Another example of ongoing research relates to the use of foam technology for tailings transport as an alternative to water transport. Spearing et al. (2001) suggest that the introduction of micro air bubbles into a dewatered tailings would permit transport of tailings in a foam medium rather than a slurry. The air could be removed at the point of discharge, if necessary, by addition of a de-foaming agent, or else roller compaction of the tailings would serve this purpose. Conceptually, a dry stack tailings deposit would be developed, but instead of using trucks or conveyors to transport the tailings, foam technology could be used. Transport costs for filtered tailings operations make up a very significant portion of the operating costs. If lower cost transport methods, such as foam technology, are shown to be viable, then the economics of dry stack tailings disposal would become more favorable than is presently the case.

The two research initiatives described above are but two of the many being undertaken by industry and academia.

6.2 *Designing for geochemical issues*

Geochemical issues became highly prominent in the last three decades as severe acid generation problems became apparent at a number of mature mines in Canada and around the world. Some of these mines, which had been operated by smaller mining companies, became orphan sites, leaving a significant legacy for the people of Canada. The majority of the acid drainage mine sites became very expensive legacies for the major mining companies that owned them. It has been necessary to develop and operate acid rock drainage (ARD) collection and treatment systems for continued operation and closure of numerous mines, one example of which is shown in Figure 13. Capital costs for ARD collection and treatment systems have been in the several tens of millions of dollars, with ongoing operating costs up to several millions of dollars annually. In Canada alone, environmental liability associated with ARD has been reported to exceed $5 billion, and worldwide liability is estimated to be as high as $100 billion (Wilson, 2001). As a result, companies developing new mines have focused on methods to predict and prevent or reduce acid generation from tailings.

Considerable research, for example CANMET's Mine Effluent Neutral Drainage (MEND) program, was carried out in the 1980’s and 1990’s, to assess viable methods of acid drainage control. The most significant conclusion of the past 20 years is that it is far easier (economic) to prevent ARD in the first place than to control it. From a number of existing sites where tailings had been placed in lakes in northern Canada, it was concluded that long term submergence of acidic wastes was probably the most effective means of ARD control. Considerable work has also been done on placement of impervious closure covers over tailings to prevent ingress of air and water. Sophisticated designs of multiple-layer covers, incorporating impervious zones, pervious capillary barriers and topsoil for vegetation growth, have been developed. Covers have been found to present the risk of long term cracking or erosion, and to be ineffective in excluding air, so are often less favored solutions than submergence from the geochemical standpoint in sites where it is feasible to maintain a submerged condition. Some of the main technologies for reduction of ARD potential from sulphide-bearing tailings are the following:

Figure 13 Lime treatment plant for neutralizing acidic mine drainage

a) Design for submergence by flooding the tailings at closure. This is a solution which is being increasingly encouraged and accepted by regulators. However, the authors are concerned that flooded impoundments may create a risky legacy. The more traditional closure configuration for tailings impoundments has been to draw down water ponds as completely as possible, to reduce the potential for dam failure by overtopping or erosion. To raise water levels in impoundments formed by high dams could present considerable long-term risk. One of the reasons that closed tailings impoundments have traditionally proven to be generally more safe, from the physical stability perspective, than operating impoundments is the relatively more "drained" condition of closed impoundments that do not include a large water pond. The flooded closure scenario represents an "undrained" condition that does not allow this improvement in physical stability to develop, so the risk does not decrease with time.

Vick (1999) describes the dam safety implications associated with the use of the submergence option in the Canadian province of Ontario versus the mining regions of Peru. In Ontario, topography is relatively subdued, tailings dams are constructed to relatively low heights, the terrain is geologically stable and not subject to frequent earthquakes, and hydrology is well understood. In other words, conditions are favorable to maintaining flooded tailings impoundments in a safe condition. Vick (1999) contrasted this to conditions in Peru, where topography is extreme, tailings dams are constructed to great heights, the terrain is geologically unstable and subject to frequent great earthquakes, and hydrology is not well understood. Further, the expertise and resources required to maintain large, water-retaining dams is not readily available in Peru. As a result, the likelihood of failure of a flooded tailings impoundment in Peru would be expected to be higher than in Ontario. As such, the wisdom of exporting the "submerged tailings solution" from Canada to other parts of the world where such technology creates unintended dam safety consequences merits careful consideration.

b) Treatment of tailings to create non-acid generating covers. To avoid the necessity of flooding impoundments, non-reactive covers of tailings can be placed on the top of the impoundment on the last few years of operation. It has been shown in several mining operations, for example at the Inco Ontario Division central milling operation in Copper Cliff, Ontario, that by the relatively inexpensive installation of some additional flotation capacity, pyrite can be removed to the level that the tailings can be made non-acid generating. The upper non-acid generating tailings placed on top can be left as a wide beach for dam safety, while the underlying mass of potentially acid generating tailings remains saturated below the long term water table in the impoundment. Normally, the small amount of pyrite removed by flotation can be disposed as a separate tailings stream, placed in the deepest part of the impoundment where it can be left flooded.

c) Evapotranspiration covers in arid climates. In many regions of the world the submergence option cannot even be considered due to the dry climate. In such areas, complex covers involving multiple low permeability and drainage layers, based on prescriptive criteria developed by the U.S. Environmental Protection Agency (EPA) have often been considered. These complex covers are expensive to construct and to maintain. A single cover layer (often termed a monofill) represents a preferred and increasingly accepted type of cover for tailings facilities in arid climates because:

- the cover is durable (i.e. no geosynthetic components, no drainage/filter components);
- it is constructed of naturally-occurring materials;
- it will have an essentially unlimited life expectancy;
- it is inexpensive to construct and to maintain; and
- this type of cover is proven technology in arid climates.

A schematic representation of an evapotranspiration soil cover, together with the water balance components, is shown below in Figure 14. During precipitation events, the cover stores moisture, subsequently releasing the moisture to evaporation and transpiration following the precipitation event. By so doing, the cover prevents infiltration from penetrating into the underlying tailings. Such covers are often termed “store and release” covers.

Dwyer (2001) describes the results of an ongoing large-scale field demonstration project in New Mexico where the effectiveness and superiority of an evapotranspiration cover (relative to other more complex and more costly types) is being demonstrated. This project is being carried out by the U.S. Department of Energy (DOE). Infiltration through a variety of covers, including complex, multiple-layer covers incorporating geomembranes and geosynthetics, is being measured in the instrumented test plots. Three years into this project, the evapotranspiration cover has yielded the most effective performance in limiting infiltration to an essentially negligible amount.

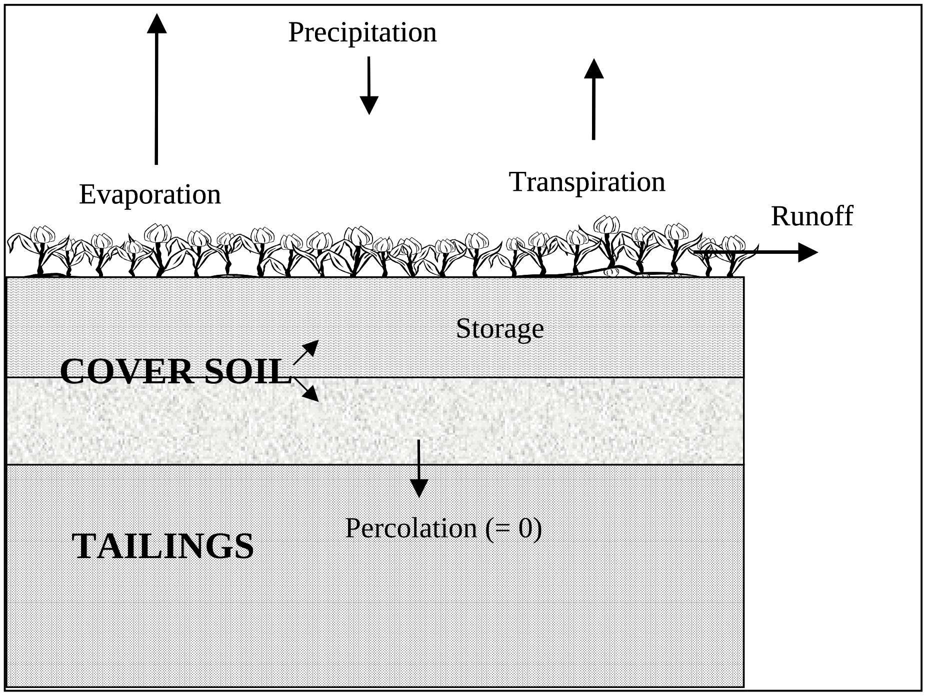


Figure 14 Schematic Representation – Evapotranspiration Soil Cover

To be effective, an evapotranspiration cover must have the following characteristics:

- sufficient fines content (particularly silt) to be of relatively low hydraulic conductivity, to provide a high moisture retention capacity, and to maximize evaporation and transpiration;
- not have an excessively high degree of plasticity (i.e. clay content) such that it would be subject to desiccation cracking; and
- of sufficient thickness such that it can store infiltration from wet periods and prevent percolation into the underlying tailings.

d) Lake or ocean subaqueous disposal. The surest, safest and most cost-effective solution to prevent ARD is sub-aqueous disposal in a lake or the ocean. Tailings will remain permanently submerged and have been shown to be non-reactive under water. However, there is disagreement as to the overall environmental impacts of this solution, so that regulators are reluctant to permit lake or ocean disposal, and there are not always appropriate sites available. In addition, the public often reacts emotionally and negatively to the concept of such disposal, despite the considerable benefits of these approaches. The authors are aware of at least two examples where public pressure incited regulators to demand that existing operations switch from ocean or lake disposal to on-land impoundments, with the result that environmental problems actually increased. The authors do note a slight trend to re-acceptance of subaqueous disposal, particularly in the marine environment, as the true environmental impact of the technique can be demonstrated to be almost negligible where favorable conditions exist. Moreover, the corporate risks and environmental liabilities associated with surface tailings storage on many projects grows to the point where project viability is threatened without looking to environmentally acceptable alternatives including subaqueous disposal.

7 RECENT TRENDS - METALLURGICAL ASPECTS OF TAILINGS MANAGEMENT

7.1 *From end of pipe to integrated approach*

In the past, tailings management was considered to begin “at the end of the pipe”, and the approach to environmental stewardship was to look to end-of-pipe solutions to problems. The metallurgical design of the plant was focused solely on maximizing recovery, and it was left to the tailings dam operator to deal with the consequences of that sole focus. Waste treatment simply meant treating whatever was left over after the process was complete. This was a reactive approach to tailings management. Industry developed innovative practices to provide end-of-pipe solutions, but in many cases this approach proved costly and reduced profitability.

Following the implementation of environmental regulations, ways and means to reduce waste treatment costs became essential to maintain profitability. The emphasis in planning shifted from waste treatment to waste management. This included waste minimization through the use of recycle, source control as well as fundamental process design changes. Waste treatment in the mining industry will always be required, due the nature of the activity. However, the quantities of waste that require additional treatment prior to disposal have dropped substantially. Typically, metallurgical and waste treatment process design is carried out on an iterative basis, with economics, technical feasibility and environmental impacts assessed at each step. As a result, tailings management no longer begins at the end of the pipe; it begins in the very design of the metallurgical extraction processes. Tailings management has therefore shifted from being reactive to being proactive. An example of this integrative approach is the application of dewatering technologies as described in Section 6.1.3. Others are described in Section 7.2. Increasingly, it is being recognized that tailings management design requires close partnership between the process engineer, the dam designer, geochemists, hydrologists and hydrogeologists. This partnership facilitates making the right decisions at the very outset of a project.

7.2 *Integrative Technologies for Tailings Management*

7.2.1 *Selective flotation to control Acid Rock Drainage*

Land disturbance, including mining activities, can expose rock containing sulphide minerals to oxygen and water, and can result in the production of sulfuric acid in a process commonly referred to as acid rock drainage (ARD). Acidic drainage can contain elevated concentrations of soluble metals and other oxidation products that can have significant environmental impact. Although selective flotation cannot be applied to all sulphide-bearing orebodies, it is a good example of how changes in mineral processing can prove effective in ARD control.

Mines producing zinc, copper and lead sulfide concentrates from porphyry deposits, use flotation processes consisting of both rougher and cleaner circuits. In the past, tailings from the rougher and cleaner circuits were combined and discharged to a tailings pond. These tailings were acid-generating, with associated potential long-term liability. Tailings from sulphide flotation typically contain high concentrations of pyrite; however, depending on the ore type and flotation process used, it is possible to get most of the pyrite to report to the cleaner circuit tailings. The tailings from the two circuits can have substantially different ARD potential. In the rougher circuit, the objective is to reject gangue material consisting of silicates and oxides, with all the sulphide reporting to the rougher concentrate. Changes to the system can however be implemented to allow for production of two different tailings streams, one-acid generating and the other not. Potentially acid-generating (PAG) tailings can be discharged through a separate tailings line and deposited in a deep section of a tailings impoundment, while non-acid generating tailings can be discharged through a second tailings line and used to the cover the ARD tailings. At closure, ARD tailings could be permanently encapsulated in non-acid generating tailings, eliminating the long-term liability associated with ARD. Although this approach will work in some cases, it is not universal, since it requires a clean separation of sulfides in the rougher circuit, which is not always attainable due to the nature of the ore.

7.2.2 *Selective flotation concentration of gold ore*

Selective flotation can be used in gold processing to reduce the quantity of ore, and thereby either eliminate or reduce the consumption of cyanide and indirectly reduce the waste being generated. Alternatively, in some cases gold-bearing flotation concentrates can be shipped off-site to a location with better facilities to treat and store wastes, thereby eliminating the potential release of reagents such as cyanide at site, where the resulting environmental impact would be unacceptable.

7.2.3 *Environmental management of cyanide*

Cyanide is used for both gold extraction via cyanidation and as a sulphide depressant in flotation. Before the mid-1970s, the form of cyanide treatment used in the mining industry in Canada was the natural degradation of cyanide-bearing wastes that occurred in tailings ponds. However, limitations associated with climate and with the construction of water-retaining structures resulted in the discharge of cyanide-bearing wastes that in many cases was unacceptable from an environmental perspective. At the time, there was often very little recycling of process water, due to the accumulation of compounds in the recycle water, which interfered with the process. This is a continuing problem.

With the promulgation of regulations in the late 1970s, many mines were required to design and construct waste treatment facilities for cyanide-bearing wastes. The waste treatment technology evolved quickly and included alkaline chlorination, SO_2-air oxidation, hydrogen peroxide oxidation and other technologies. Concurrently, a number of other process changes were implemented in gold processing and flotation to reduce environmental impact:

- Recycle Systems

Water was commonly recycled from the tailings impoundment with subsequent re-use in the grinding circuit. Coupled with the treatment of both tailings and any excess process water, recycle systems substantially reduced the quantities of cyanide-bearing waste being released to the environment. However, recycle water quality has to be monitored carefully. In some cases, the treatment of recycle water may be a preferable alternative to overcome water quality problems and thus potentially reduce the amount of final effluent water being discharged.

- Anti-Scaling Compounds

Anti-scaling compounds have been used in some recycle systems to reduce the impact on the process of residual compounds in the recycled water such as sulphate.

- Gravity Concentration

Gravity concentration systems can be added to the front end of a mineral processing circuit to separate a portion of the coarse gold in a given ore. This can reduce cyanide consumption, thereby reducing the amount of waste requiring treatment and associated by-products. The increased application of gravity concentration in mineral processing has been enhanced by the recent development of new gravity concentration devices.

- Pretreatment

Pretreatment technologies such as aeration, pressure oxidation, bio-leaching and chemical oxidation are used to reduce cyanide consumption and improve process efficiency with refractory ores. In the past, these types of ore, would consume high levels of cyanide, with the resultant production of large amounts of cyanide degradation products.

- Alternative Reagents for Gold Processing

Reagents such as thisophates and thiourea have been investigated to replace cyanide in gold processing; this has possible environmental benefits. To date however, none of these reagents have proven commercially viable.

The traditional use of cyanide to depress pyrite in flotation has been replaced in many cases by other reagents. In addition, changes in the flotation process itself have resulted in substantial reductions in the concentrations of cyanide used.

8 CONCLUDING REMARKS

Figure 2 presented a summary of sufficiently well documented "significant" tailings dam failures over the 20th century. From the summarized information in Figure 2, two possible trends are shown and are labeled A and B. Using Figure 2 as a barometer, what is the likely future for tailings dam performance? Is the trend to be like A; either remaining at roughly 2 or more significant failures per year with a gradual increase and perhaps also having the occasional particularly "bad" decade (like the 1970's)? Alternatively, will the trend of an apparent decrease in failures since the 1970's suggested by line B continue into this new century? The demands of the public, regulators, financial institutions, and the self-interest of the mining industry clearly demands the latter. The same holds true for less dramatic environmental failures of tailings impoundments.

An optimistic response, e.g. a B trend, is possible with a commitment from the entire industry to an adherence to fundamentally sound stewardship concepts; and the authors are cautiously optimistic as this commitment is growing rapidly. Achieving a B trend will be a challenge if for no other reason that, as the population of tailings dams increases, and the frequency of failures remained the same, the number of failures would still increase with time. This cannot be allowed to happen, and the industry needs to strive for a failure rate as low as, if not lower, than the owners of conventional water storage dams.

The most positive trend is that it is the mining industry itself that is leading the drive towards achieving good stewardship practices. There will inevitably be a time lag between the identification of internationally-accepted good stewardship practices, and their implementation. Given the focus on this issue, the mining industry must make their rapid implementation a high priority.

The stakeholders in responsible and effective stewardship of tailings facilities include:

1. Owners
2. Operators
3. Designers
4. Regulators
5. Public individuals or collectives

The authors suggest some minimum expectations for each of these stakeholder groups in achieving these objectives.

Owners – Recognize the importance of good management principles and practices with regards to tailings stewardship. Responsible stewardship of tailings facilities costs money, but it is money well spent. Move from an end-of-pipe approach to tailings management to a more integrative approach, recognizing that effective tailings management must begin in the extraction process, not at the end of the pipe. Recognize the critical importance of making the right decisions at the outset of a project, and account for long-term closure costs and liabilities in financial evaluations of existing and potential projects. Making the right decisions depends on the quality of the baseline data collected, so ensure that these studies are comprehensive. Recognize that focus only on up front capital costs at the expense of the long-term view can result in decisions being made that have long-term adverse consequences. Only retain design assistance from reputable designers with track records that can be verified. Don’t get sold by smooth claims of success, check a designer’s background and with some of their former clients. This due diligence can save a lot of future difficulties. Support ongoing research projects that seek to produce less waste and more physically and chemically stable tailings deposits. Senior mining companies should consider providing mentoring for junior companies in terms of stewardship of tailings facilities, to bring all players in the industry to the same level. Have submitted designs checked by independent professionals. Give serious consideration to retaining third-party review as part of a periodic audit process, recognizing that this is a means of building trust with regulators and with the public. During operations, have a qualified person charged with tailings dam stewardship and provide that individual with the authority to retain professional assistance as deemed necessary. For older operations, be diligent in assessing the history of the operation - look for forgotten "incidents" involving tailings dam management.

Operators - make certain you have an Operations Manual to guide you in the stewardship of your facility. If one does not exist, demand one. Maintain contact with the designer. Become educated on the surveillance requirements for your facility: understand not just what to look for, but why it is important in the context of design and operating requirements. Finally, do not allow a design to be imposed on you without your active participation. Object loudly when you are given a design that is not practical for operation. Recognize the importance of tailings facility stewardship, make it a priority, assign competent individuals to the task, and provide them the resources needed to do their jobs.

Designers – Do not work out of your area of competence and/or experience. This includes not using "off the shelf" designs that may have been successful for you in the past but are possibly woefully inappropriate for the climatic/tectonic/foundation conditions for the project at hand. Do not assume that you will be able to "make it work" just because you were able to obtain a given contract. Commercial successes should not breed overconfidence in your design capabilities. The case history database indicates that most of the recent failures involved designs from either "well-known" designers and/or large, seemingly reputable organizations. Welcome and encourage independent review - do not view such as an attack on your design and/or competency but a benefit to you as much as your client. Assist the industry in moving from an end-of-pipe approach to an integrative approach, through incorporation of geochemical issues and tailings handling technologies. Design for secure closure, recognizing that "perpetuity" is a long time, and that there is little experience in designing dams to last "forever". Ensure that you work in partnership with the operators, and that your design requirements are compatible with the requirements and capabilities of the facility operators.

Regulators - establish/maintain a database on all tailings dams, operating and otherwise, within your jurisdiction. Maintain candid assessments of the performance records of owners and designers and share such details with other regulators as appropriate. Facilitate developments where the owner presents an independently reviewed design that is consistent with standard design criteria. Work to repeal regulations that are incompatible with common sense. It is not your job to make the industry fail but to assist in its stewardship efforts.

Public Participants – Recognize the vital importance of the mining industry to modern society and to the economies of developing countries, and that elimination of mining must eventually mean a return to a Paleolithic lifestyle. Continue to expect responsible stewardship of the environment by this essential industry. Acknowledge that the vast majority of mining industry operators and operations deserve praise for their efforts. Concentrate on factual accounts of incidents to develop and maintain credibility. Avoid supporting non-government organizations that endorse actions against corporations committed to a high degree of environmental stewardship and who operate their mines and tailings facilities accordingly.

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