Trends in the stewardship of tailings dams

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ABSTRACT: Tailings impoundments frequently represent the most significant environmental liability associated with mining projects, both during the operational and decommissioning phases of a project. 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. Frequently, the seeds for such incidents are sewn as a result of a combination of design flaws and inadequate stewardship practices. Proper stewardship is critical in that, through implementation of quality assurance practices such as independent peer review of designs or risk assessments, it can protect the owner from faulty designs. For proper designs, good stewardship provides a tailings facility designer with reassurance that the facility will be constructed, operated, and monitored in accordance with that design.

This paper discusses recent trends in the stewardship of tailings facilities, both in Canada and world-wide. These include proactive initiatives by industry associations, and individual mining companies specifically addressing stewardship issues. The paper also discusses the roles that tailings dam design consultants can play in assisting the mining industry in this regard.

1 INTRODUCTION

Tailings dams 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 largely biased and sensationalized reporting in the media. These recent failures, together with previous ones, have put the mining industry under increasing pressure and scrutiny in regard to the safety of tailings impoundments. 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, unfortunately is often repeated by many today, in spite of the enormous benefits that mining has and continues to provide society. The mining industry response to this blind criticism can only be that its tailings facilities are well-designed and are well-managed. 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.

For the purposes of this paper, stewardship is defined as the direction and implementation of all design (conceptual through detailed), construction, operations, inspection, surveillance, review, and managerial aspects (corporate policies, training, roles and responsibilities, documentation and reporting, etc.) involved in seeing a tailings facility through from conceptual design through closure. No one of these issues can be said to be more important than another (Szymanski, 1999). This paper will focus primarily on those aspects of stewardship of facilities that apply once a tailings facility is in operation.

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. In addition, 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 evolving practice and initiatives related to the stewardship of tailings facilities. Stewardship is of equal significance to technical design aspects because under proper stewardship design errors can be detected and, in some instances, prevented from manifesting themselves as failures. However, no stewardship will be sufficiently robust to cover for all potential design flaws, and no design is sufficiently robust for the most negligent stewardship.

The initiatives discussed in this paper have been spear-headed by regulatory agencies, the United Nations Environment Programme (UNEP), the Canadian Dam Association (CDA), the Mining Association of Canada (MAC) and, most importantly, individual mining companies. The importance of the mining industry, and individual mining companies, leading these efforts cannot be overstated, because if the industry cannot properly manage its tailings facilities, then someone else (e.g. regulators) may impose proper management. More failures will serve to strengthen the hand of mining's detractors. Tailings dam design consultants can take a significant role in assisting mining companies in development and implementation of proper stewardship programs.

2 TAILINGS DAM FAILURES – A BRIEF REVIEW AND PERSPECTIVE

Tailings dam failures are, despite the recent spate of publicity, rare events that are unrepresentative of modern mining industry success in safe tailings disposal. The reporting of such events is incomplete and heavily biased, and there is no worldwide database of failures, nor is there one in Canada. This is illustrated by Figure 1, 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 1. 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 2 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, and the 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. Figure 2 also indicates that the future trend may continue to project downward, but this is dependent on the continuation and implementation of improving stewardship practices.

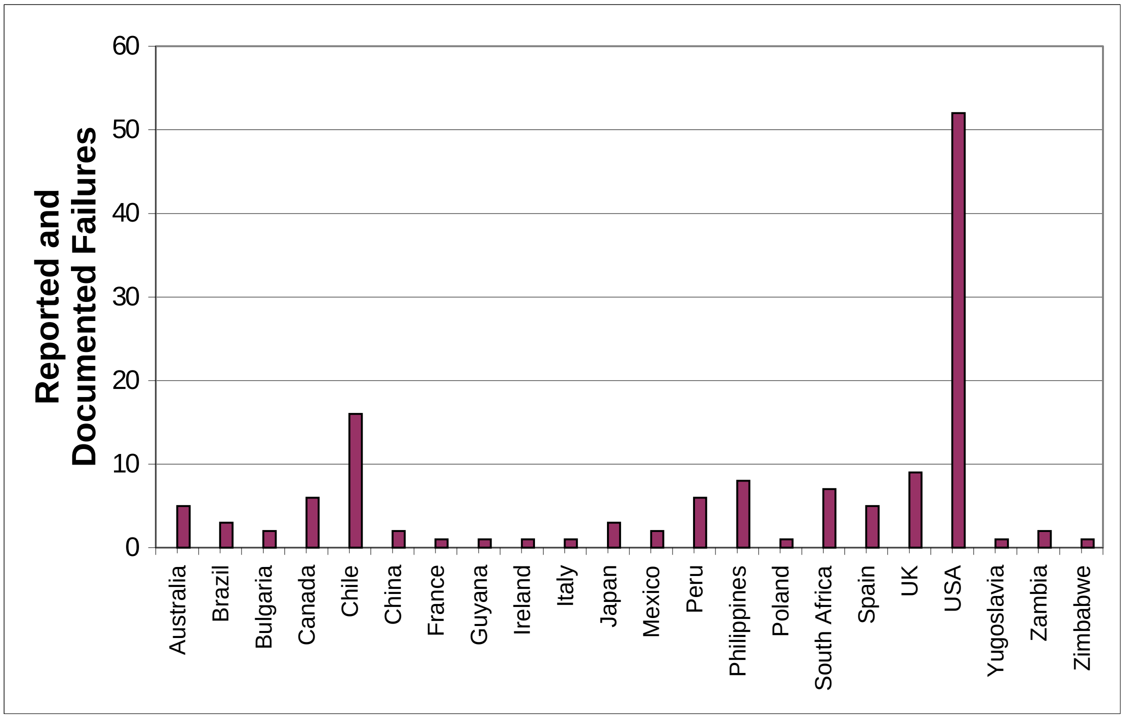

Figure 1. Tailings Impoundment Failures by Country (USCOLD, 1994 and UNEP, 1996)

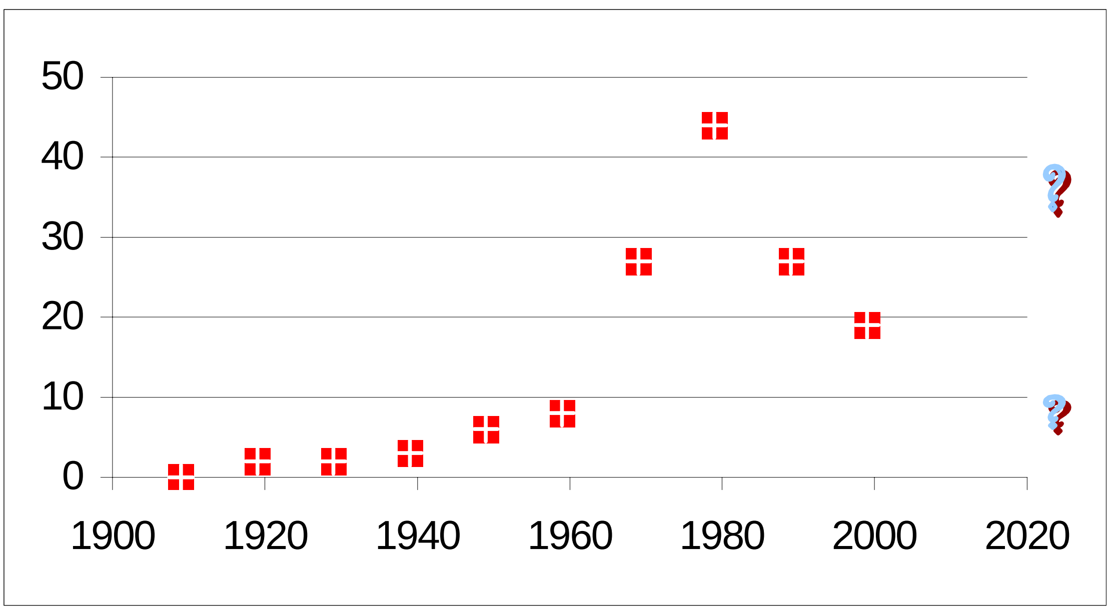

Figure 2. Frequency of Significant Tailings Impoundment Failures (USCOLD, 1994; UNEP, 1996 and authors' files)

It is estimated that there are in the order of 3500 active tailings impoundments worldwide. 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 implementation of these practices, the favorable downward trend should continue to the point that the frequency of tailings dam failures (normalized to the number of tailings dams in existence) is no higher than that of conventional dam failures (see Figure 3). This is an ambitious goal given that tailings dams must last for hundreds of years, while conventional dams have a shorter design life. Therefore, it can be argued that the number of conventional dams worldwide could remain the same, while the number of tailings impoundments will increase. This increase, in terms of tailings dam safety, is particularly significant given that the water cover option is so often selected for tailings dam closure. In many cases, a low permeability tailings dam without the water cover option still has roughly the same attributes as a dam with the water cover.

3 UNIQUE FEATURES OF TAILINGS DAMS

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. To properly understand the specific requirements for stewardship of tailings facilities, it is necessary to consider the unique features of tailings dams relative to 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.

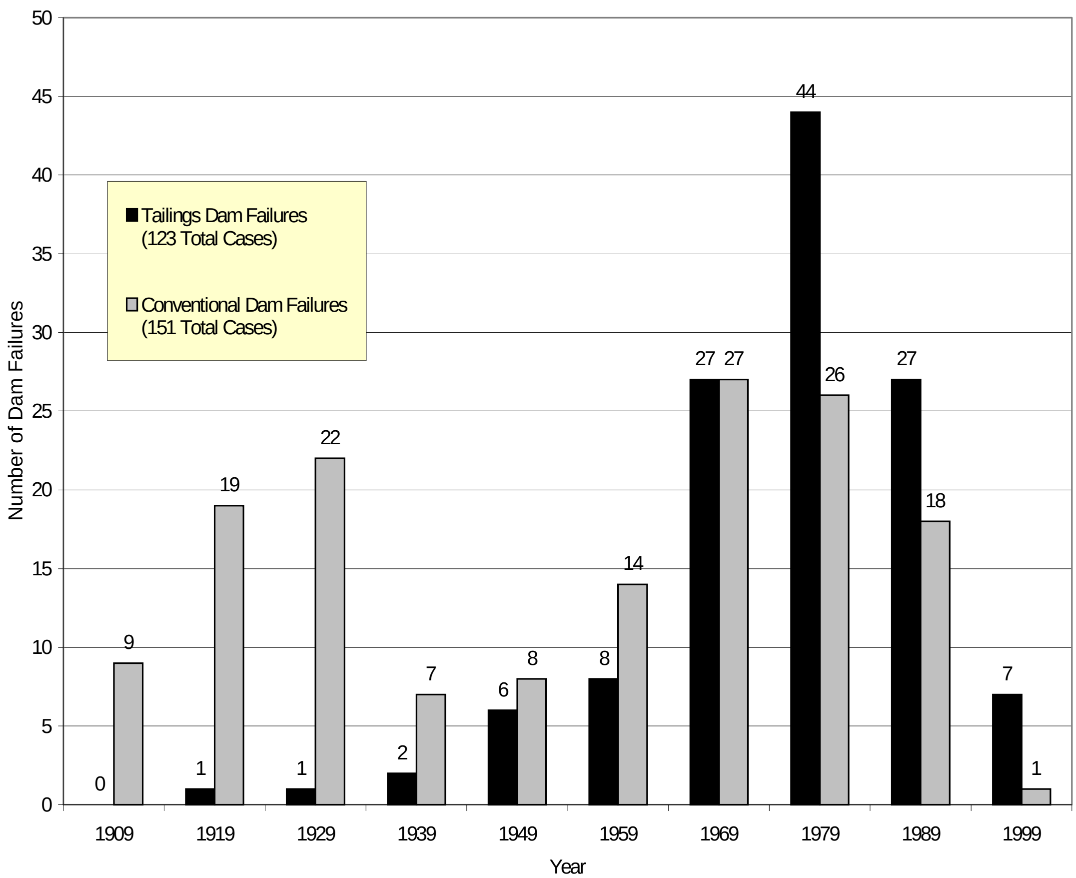

Figure 3. Tailings Dam Failures vs. Conventional Dam failures (ICOLD, 1995)

- 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.
- 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. Their condition, safety, construction, and operating practices must therefore be monitored and re-evaluated on a continuous basis, whereas these requirements for conventional dams are less demanding.
- 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, so their construction, operation, and maintenance receives a high degree of attention from owners, who often retain in-house dam engineering expertise. Contrast this to tailings dams, which are often viewed by their owners as an unprofitable, money-draining part of the mining operation, and as a "necessary evil". 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. Mining companies typically do not retain in-house dam engineering expertise, relying instead on consultants
- 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.
- Conventional dams generally do not need to be designed to last forever, as they have a finite life. Tailings dams, in contrast, because they have a closure phase as well as an operational phase, have to be essentially 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 RECENT INITIATIVES AND TRENDS

4.1 *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, is very valuable, providing a framework of management principles, policies, and objectives, and checklists for implementing the framework through the life cycle of a tailings facility. It is general in nature, but this is a strength in that it recognizes the need for individual mining companies and mining operations to establish their own specific programs that meet their own specific needs.

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.

4.2 *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)

4.3 *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 published 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 is discusses failure modes for different dam types, which is of benefit in scoping out requirements for a dam safety program, particularly dam surveillance.

4.4 *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 in that they demonstrate how the inadequacies in the management aspects of the stewardship of the tailings dam allowed the technical factors that caused the failure to develop. 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. The authors are aware of numerous such 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 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.

4.5 *Initiatives by Mining Companies*

4.5.1 *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. The following sections discuss some representative examples of proactive stewardship policies and practices being followed by mining companies.

4.5.2 *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 it.

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.

4.5.3 *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 of great import 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 in the Phillipines, 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'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.

Other mining companies have implemented similar risk assessment programs for many of their tailings facilities, including Cominco, Breakwater Resources, and Rio Tinto, to name but a few.

4.5.4 *Geotechnical 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, 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, 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.

4.5.5 *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. Had the 1991 incident progressed off-site, it is without doubt that the community response would have been dramatically different.

The authors are aware of another tailings impoundment, in operation for over fifty years, that 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. Good record keeping, and maintaining those records in good and easily accessible order, is an important aspect of stewardship of tailings facilities.

From carrying out more than 30 risk assessments of tailings dams 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" (TDA) and will repeat costly studies, ignore essential design criteria or unknowingly re-invent a tailings management plan without appreciation of the "forgotten" earlier information. Maintaining the same consulting organization does not seem to stem the onset of TDA unless the mine itself is an active partner in tailings dam stewardship. The authors' review work also shows that tailings dams that have had "incidents" in their past are often remarkably well-placed to have them occur in the future.

4.5.6 *From audits to operations manuals to implementation*

On August 29, 1996, a portion of an upstream-constructed tailings dam collapsed at the Porco Mine in Bolivia, owned by Compania Miñera del Sur S.A. (COMSUR), with a resultant release of 400,000 tonnes of tailings. Following this incident, COMSUR 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 COMSUR, 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. Based on observations made by one of the authors during the site visits, training seminars on environmental monitoring, tailings management and surveillance of tailings facilities were developed, specific to 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, and, equally as important, 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 inter-active 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. This certainly was the case for the COMSUR tailings facilities. The Operations Manuals were drafted to capture 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 plan 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.

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.

4.6 *The Role of Tailings Dam Design Consultants*

4.6.1 *General*

Tailings dam 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. Consultants obviously have common cause with the mining industry in this regard, and the following sections discuss a number of ways consultants have, are, and should be contributing to this effort.

4.6.2 *Publications and participation in conferences*

Tailings dam consultants 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 benefit. Conferences such as the annual Tailings and Mine Waste series 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, 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 tailings dams. Issues related to good stewardship are discussed throughout.

4.6.3 *The design product*

The design product provided by tailings dam engineers to the owner is, all too often, rich in discussion of the finer points of soil mechanics, but poor in terms of detailed guidance for 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.

4.6.4 *Risk assessments*

Consultants are increasingly applying techniques that can be broadly categorized as “risk assessments” to various facets of tailings management, most notably in reviews of existing facilities. Mining companies are also applying such techniques in the stewardship of their tailings facilities. A risk assessment, 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?

The authors have made frequent use of 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. Risk assessment 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) that 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 exception of failures triggered by earthquakes or major storm events, all 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.

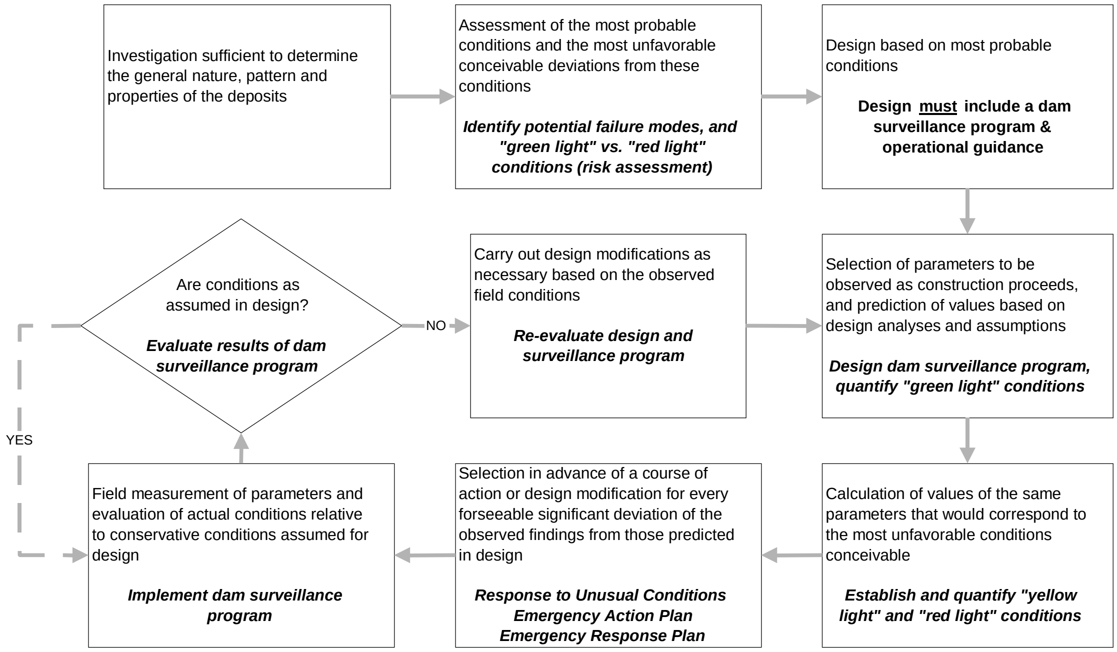

Figure 4. Risk assessments and the observational approach applied for dam surveillance

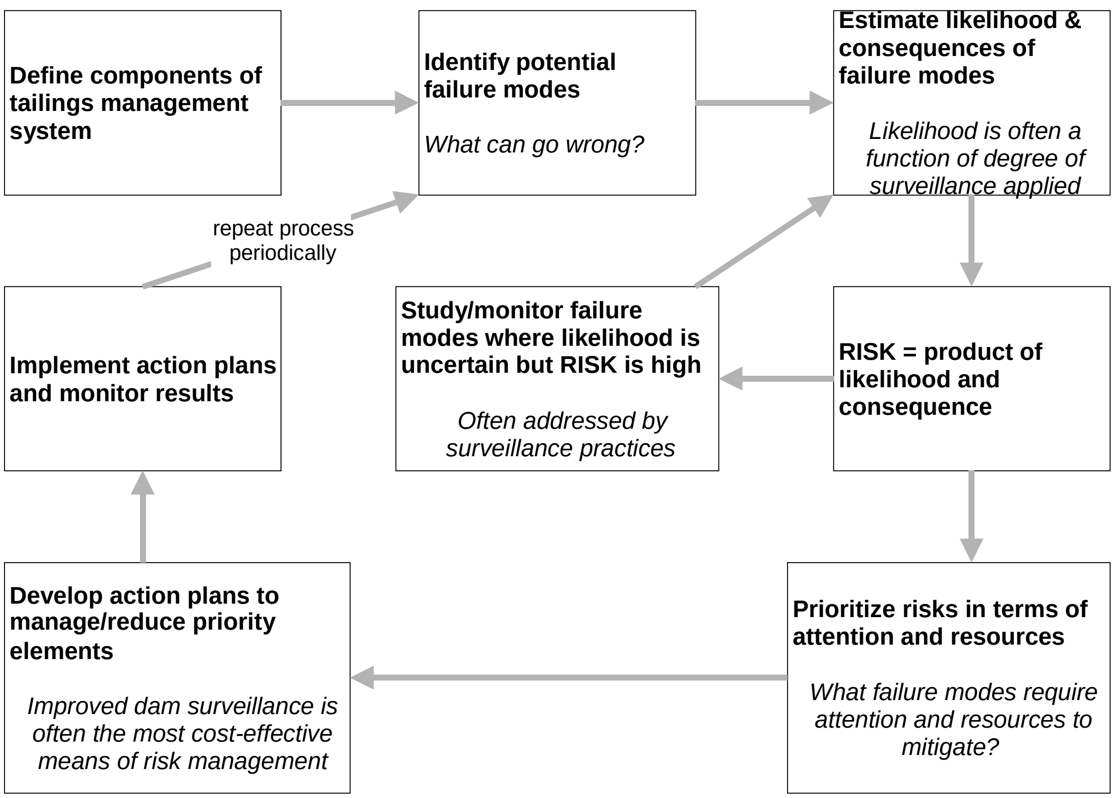

Figure 5. Risk assessment process

4.6.5 *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. Further, 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.

4.6.6 *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) and owners should share information with one another as much as possible regarding design consultants. It is an unfortunate 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.

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. 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. Peck (1980) pointed out that theory can inhibit judgement if used without discrimination and without critical evaluation. The following excerpt from a government inquiry into why the United States intelligence services were "caught napping" at Pearl Harbor stands as a poignant warning to design consultants entranced by the finer points of theory at the expense of practicality and case history experience:

> "Science was king, and his subjects were suspicious of anything that could not be observed under a microscope or demonstrated in repeated laboratory tests. The imaginative interpretation of intelligence is much more an art than a science. So the American intelligence community as scientists triumphed in technology and cold logic – magic and cryptanalysis – while as artists it failed in interpretation of the facts thus gathered."

4.7 *Regulatory Trends*

4.7.1 *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, and constraints. So much of stewardship relates to the corporate and mine-specific organizations and personnel, aspects that cannot be regulated.

4.7.2 *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 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 companies 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 in tailings dam engineering on the part of the regulators, and due in part to their understandable desire to have tailings facilities in their respective countries conform to "international" (i.e. ICOLD) standards, which really do not exist in any tangible, readily-referenced form. This is a misguided trend, because it 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 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 in this regard. The mining industry, and its consultants, could be of great assistance to regulators in developing countries by providing training and workshops for regulatory personnel responsible for tailings facilities. 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.

4.7.3 *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. 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 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 too is a welcome trend. The mining community is now international, and includes mining companies, its consultants, and regulators. The more these three bodies can assist one another in facilitating good stewardship practices, the better off everyone will be.

5 CONCLUSIONS

The safety of tailings impoundments is inextricably linked to the stewardship practices applied to their management and operation, from the concept stage through to closure. Positive and proactive trends in stewardship of tailings dams, initiated primarily by the mining industry as a whole and by individual mining companies, provide the basis for considerable optimism that the trend of decreasing tailings dam failures will continue. Tailings dam design consultants can and should be of considerable assistance to the industry in this regard, placing as much emphasis and effort on stewardship issues as on technical issues in their practice. The goal of the industry, its consultants, and regulators must ultimately be to endure fewer failures than their colleagues dealing with conventional dams, and to demonstrate and publicize mining industry successes to regulators and the public.

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Tailings dams in WA, SA, NT and Queensland have all been found to have the highest public safety risk in the case of failure. Some of the identified mines have recently been approved for expansions. A Mount Isa Mines spokesperson said the ratings refers to the "potential maximum consequence â€" not the likelihood". The audits followed the devastating collapse of Brazil's Brumadinho iron ore mine in January 2019 which resulted in 230 deaths.Â Rural news in your inbox? Subscribe for the national headlines of the day. A rating of 'high risk' is considered to have the potential to cause the deaths of 10 or more people, with the next category of 'extreme risk' having the potential to cause the deaths of 100 or more people. Australian dams considered high to extreme risk included They inform dam design, surveillance and reviews. Tailings Facilities in the portfolio.Â â€¢ A dam is a barrier constructed for the retention of water, water containing any other substance, fluid waste, or tailings1. â€¢ Tailings dams are designed and operated differently to conventional dams. â€¢ A tailings storage facility, is not yet a formally defined term.Â This study represents one of the most recent analyses of dam failure trends. Tailings dam failures1, 2. (Number of records) 30. The New Cornelia tailings Cu tailings dam in Arizona is said to be the largest dam structure (by volume) in the USA, with a capacity of 29 Mm3 and a diameter of 2.5 km (Engels and Dixon-Hardy, 2012). Even the relatively small tailings impoundment at the Lisheen Pbâ€"Zn mine in Tipperary, Ireland, was constructed with a planned capacity of over 5 Mm3 (Dillon et al., 2004). Tailings dams are commonly constructed from readily available local materials, rather than the concrete used, for example, in water-retention dams. Construction of tailings dams accelerated after World War II. At least 43 dams opened each decade between 1940 and 1960. According to the reported data, the first tailings dam located in Australia was built in the 1950s. South America. In the 1970s and 1980s, 78 dams were reportedly built in Brazil, Peru, Bolivia and other South American countries.Â The Church of England released initial findings that show about a tenth of tailings dams in the reported dataset have had stability issues. The church said it plans to share the entire dataset in early 2020. Several factors are used to classify a damâ€™s risk, including its height, slope, terrain and nearby seismology. A tailings dam is typically an earth-fill embankment dam used to store byproducts of mining operations after separating the ore from the gangue. Tailings can be liquid, solid, or a slurry of fine particles, and are usually highly toxic and potentially radioactive. Solid tailings are often used as part of the structure itself. Tailings dams rank among the largest engineered structures on earth. The Syncrude Mildred Lake Tailings Dyke in Alberta, Canada, is an embankment dam about 18 kilometres (11 mi)