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TECHNICAL REPORT

DESIGN AND EVALUATION OF TAILINGS DAMS

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DISCLAIMER AND ACKNOWLEDGEMENTS

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Sections of this document rely heavily on Steven G. Vick's *Planning, Design, and Analysis of Tailings Dams* (BiTech Publishers Ltd. 1990). This is particularly true of certain concepts and organizational emphases, as well as many of the tables and figures. In some cases, this document presents a digest of Vick's overall approach to tailings dam planning and design. Permission to use *Planning, Design, and Analysis of Tailings Dams* as a major source was provided by Mr. Vick, who is not responsible for any errors of omission or interpretation in the present document.

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1. INTRODUCTION

In order to obtain the metals and other minerals needed for industrial processes, fertilizers, homes, cars, and other consumer products, large quantities of rock are mined, crushed, pulverized, and processed to recover metal and other mineral values. A fine grind is often necessary to release metals and minerals, so the mining industry produces enormous quantities of fine rock particles, in sizes ranging from sand-sized down to as low as a few microns. These fine-grained wastes are known as "tailings."

Until recent decades, the majority of mines were small underground operations with correspondingly modest requirements for tailings disposal. Since that time, due to increasing demand, it has become economical to mine large lower-grade deposits by utilizing advances made by mining equipment manufacturers and developments in mining and milling technology. This has greatly increased the amount of tailings and other wastes generated by individual mining projects and by the mining industry as a whole.

There are approximately 1,000 active metal mines in the United States (Randol, 1993) Many of these have at least one tailings impoundment and often several impoundments grouped together in cells. EPA estimates that there may be several thousand tailings impoundments associated with active non-coal mining, and tens of thousands of inactive or abandoned impoundments.

By far the larger proportion of ore mined in most industry sectors ultimately becomes tailings that must be disposed of. In the gold industry, for example, only a few hundredths of an ounce of gold may be produced for every ton of dry tailings generated. Similarly, the copper industry and others typically mine relatively low-grade ores that contain less than a few percent of metal values; the residue becomes tailings. Thus, tailings disposal is a significant part of the overall mining and milling operation at most hardrock mining projects. There are several methods used for tailings disposal. These include disposal of dry or thickened tailings in impoundments or free-standing piles, backfilling underground mine workings and open-pits, subaqueous disposal, and the most common method, the disposal of tailings slurry in impoundments. Modern tailings impoundments are engineered structures for permanently disposing of the fine-grained waste from mining and milling operations. At some projects, tailings embankments reach several hundred feet in height and the impoundments cover several square miles.

Historically, tailings were disposed of where convenient and most cost-effective, often in flowing water or directly into drainages. As local concerns arose about sedimentation in downstream watercourses, water use, and other issues, mining operations began impounding tailings behind earthen dams, which were often constructed of tailings and other waste materials. The impoundments served the dual purpose of containing the tailings and, particularly in the arid west, allowing the re-use of scarce water.

More recently, concerns have been raised about the stability and environmental performance of tailings dams and impoundments. Stability concerns are raised in part by the use of tailings material in tailings dams/embankments; to mitigate these concerns, such embankments often rely on a certain amount of controlled seepage to enhance stability, which in turn affects environmental performance. Ritcey (1989) has speculated that the need for sound impoundments in the uranium industry "probably" accounts for much of the recent attention paid to impoundment design in other types of facilities. Perhaps triggered by the initial attention to uranium impoundments, the increasing concern for environmental performance has led to better engineering design of tailings dams in other mining industry sectors, for both stability and environmental performance. For instance, experience gained with leach pad liners is being transferred to linings for tailings ponds, and the use of synthetic lining materials is growing (although use of liners is still far from being the industry norm). In addition, the use of cyanide and other toxic reagents in mill processes has raised special concerns for some tailings and is leading to increased treatment prior to disposal as well as increased attention to containment. Finally, continuing concerns over acid mine drainage is resulting in a growing body of research and emerging concepts of long-term control or mitigation.

Inactive tailings impoundments also are receiving more attention due to the long-term effects of windblown dispersal, ground water contamination, and acid drainage. In many cases, the costs of remediation can be considerable, exceeding the costs of original design and operation of the tailings impoundment.

While this report discusses general features of tailings dams and impoundments, actual designs for tailings disposal are highly site-specific. Design depends on the quantity and the individual characteristics of the tailings produced by the mining and milling operation, as well as the climatic, topographic, geologic, hydrogeologic and geotechnical characteristics of the disposal site, and on regulatory requirements related to dam safety and to environmental performance. What may work for one type of tailings may not work for another type, and may not work for the same tailings at different sites. Hence each situation requires its own design process. The estimated quantity of tailings to be disposed of is particularly important given the evolving nature of most mining projects. Tailings quantity estimates are based on estimated reserves that change continuously as mine development progresses. Accordingly, the final size and design of tailings impoundments can differ substantially from initial projections. This presents major challenges to Federal land managers and State permit writers, who are faced with reviewing and overseeing tailings impoundment planning, design, and performance, and to the general public, who may ultimately pay for miscalculations resulting in environmental damages.

The purpose of this report is to provide an introduction for Federal land managers, permit writers, and the general public to the subject of tailings dams and impoundments, particularly with regard to their engineering features and their ability to mitigate or minimize adverse effects to the environment. The report is based on the current literature on tailings impoundment engineering. While broad in scope, the report is necessarily limited in depth: a comprehensive guide to the design and evaluation of tailings impoundments would incorporate most of the materials in a number of examinations of tailings dam engineering and environmental performance, including those in texts by Vick (1990), Ritcey (1989), and CANMET (1977), among others.

It should also be noted that tailings dam engineering is continually evolving. The relatively recent emphasis on environmental performance is leading to many changes in the field, many of which are as yet not fully tested. Vick (1990) may be the most recent and most comprehensive examination of the topics covered by this report. Consequently, certain sections of this report rely heavily on Vick's approach.

The next section of this report provides an overview of the various methods used to dispose of mine tailings and the types of impoundments that are used. Section 3 describes the basic concepts used in the design of impoundments, including a number of site-specific variables of concern. Section 4 discusses tailings embankment and stability, while Section 5 briefly discusses water management in tailings impoundments. A case study on a lined tailings impoundment is presented in Section 6. Finally, Section 7 lists all references cited in the text.

2. OVERVIEW OF TAILINGS DISPOSAL

The ultimate purpose of a tailings impoundment is to contain fine-grained tailings, often with a secondary or co-purpose of conserving water for use in the mine and mill. This has to be accomplished in a cost-effective manner that provides for long-term stability of the embankment structure and the impounded tailings and the long-term protection of the environment. In the process of designing any tailings embankment and impoundment, these three interests, cost, stability, and environmental performance, must be balanced, with situation-specific conditions establishing the balance at each stage of the process. It is worth noting that the long-term costs of tailings disposal depend in part on mechanical stability and environmental integrity, such that stable and environmentally acceptable structures promote cost effectiveness.

Impoundment of slurry tailings is the most common method of disposal and are the main focus of this report. Impoundments are favored because, among other things, they are "economically attractive and relatively easy to operate" (Environment Canada 1987). Tailings impoundments can be and are designed to perform a number of functions, including treatment functions. These include (Environment Canada 1987):

- Removal of suspended solids by sedimentation
- Precipitation of heavy metals as hydroxides
- Permanent containment of settled tailings
- Equalization of wastewater quality
- Stabilization of some oxidizable constituents (e.g., thiosalts, cyanides, flotation reagents)
- Storage and stabilization of process recycle water
- Incidental flow balancing of storm water flows.

There are, however, a number of disadvantages to tailings impoundments requiring attention in design, including (Environment Canada 1987):

- Difficulty in achieving good flow distribution
- Difficulty in segregating drainage from uncontaminated areas
- Difficulty in reclamation, particularly with acid-generating tailings, because of the large surface area and materials characteristics
- Inconsistent treatment performance due to seasonal variations in bio-oxidation efficiency
- Costly and difficult collection and treatment of seepage through impoundment structures
- Potentially serious wind dispersion of fine materials unless the surface is stabilized by revegetation, chemical binders, or rock cover.

2.1 Methods for Tailings Disposal

Because mine tailings produced by the mill are usually in slurry form, disposal of slurry tailings in impoundments made of local materials is the most common and economical method of disposal. There are four main types of slurry impoundment layouts; valley impoundments, ring dikes, in-pit impoundments, and specially-dug pits (Ritcey 1989). These impoundment configurations are explained in more detail below, with major emphasis on valley impoundments, as they are the most common. Before describing impoundments, several other methods of tailings disposed are briefly described below.

In some cases, tailings are dewatered (thickened to 60 percent pulp density or more) or dried (to a moisture content of 25 percent or below) prior to disposal. The efficiency and applicability of using thickened or dry tailings depends on the ore grind and concentrations of gypsum and clay as well as the availability of alternative methods. Except under special circumstances, these methods may be prohibitively expensive due to additional equipment and energy costs. However, the advantages include minimizing seepage volumes and land needed for an impoundment, and simultaneous tailings deposition and reclamation. (Vick 1990)

Slurry tailings are sometimes disposed in underground mines as backfill to provide ground or wall support. This decreases the above-ground surface disturbance and can stabilize mined-out areas. For stability reasons, underground backfilling requires tailings that have a high permeability, low compressibility, and the ability to rapidly dewater (i.e., a large sand fraction). As a result, only the sand fraction of whole tailings is generally used as backfill. Whole tailings may be cycloned to separate out the coarse sand fraction for backfilling, leaving only the slimes to be disposed in an impoundment. To increase structural competence, cement may be added to the sand fraction before backfilling (Environment Canada 1987).

Open-pit backfilling is also practiced, where tailings are deposited into abandoned pits or portions of active pits. The Pinto Valley tailings reprocessing operation, located in Arizona, uses this method to dispose of copper tailings. In active pits, embankments may be necessary to keep the tailings from the active area. However, since seepage from the tailings can adversely affect the stability of the pit walls or embankments, it is unusual to see disposal in active pits. Williams (1979), for example, discusses a failure due to pore water pressure in the floor of a pit in Australia. Ritcey (1989) notes that the hydrogeological parameters affecting the migration of seepage and contaminants are poorly understood, so tailings with toxic contaminants or reactive tailings may be poor candidates for this type of impoundment. The U.S. Bureau of Mines points out that other limitations for using active open pits for tailings disposal are loss of the pit areas for future resources, and subsequent mine operating and design restrictions to which mine operators would be subjected.

Subaqueous disposal in a deep lake or ocean is also a possible disposal method. Underwater disposal may prevent the oxidation of sulfide minerals in tailings, thus inhibiting acid generation. Subaqueous disposal has recently been practiced by eight mines in Canada, with three still active as of 1990 (Environment Canada 1992). Subaqueous disposal is used in areas with high precipitation, steep terrain, or high seismicity or, in Canada, where its use predated current regulations. This method is also limited to coarse tailings that can settle quickly. CANMET (Canadian Centre for Mineral and Energy Technology) completed a bench-scale 16-year simulation of deep-lake disposal using Ottawa River water (Ritcey and Silver 1987). They found that the tailings had little effect on pH when using ores with a low sulfide content. Ripley, et al. (1978), found that the tailings can cover large areas on the ocean or lake floor and cause turbidity problems if the disposal practice is not designed correctly. There is little data on the long-term effect of subaqueous disposal (Environment Canada 1987), although it is being studied in Canada and peer reviewed by CANMET (CANMET 1993).

A variation on subaqueous disposal in the ocean or lakes would be permanent immersion of tailings in a pit or impoundment. This could present many of the same advantages of underwater disposal (i.e., reduced oxidation of sulfide minerals) but also would require long-term attention to ensure constant water levels and possibly monitoring for potential ground water impacts.

2.2 Types of Impoundments

There are two basic types of structures used to retain tailings in impoundments, the raised embankment and the retention dam. Because raised embankments are much more common than retention dams, they are emphasized in this report. Either type of structure, raised embankments or retention dams, can be used to form different types or configurations of tailings impoundments. The four main types of impoundments include the Ring-Dike, In-Pit, Specially Dug Pit, and variations of the Valley design. The design choice is primarily dependent upon natural topography, site conditions, and economic factors. Most tailings dams in operation today are a form of the Valley design. Because costs are often directly related to the amount of fill material used in the dam or embankment (i.e., its size), major savings can be realized by minimizing the size of the dam and by maximizing the use of local materials, particularly the tailings themselves.

Retention dams are constructed at full height at the beginning of the disposal whereas raised embankments are constructed in phases as the need for additional disposal capacity arises. Raised embankments begin with a starter dike with more height added to the embankment as the volume of tailings increases in the impoundment.

Tailings retention dams (Figure 1) are similar to water retention dams in regard to soil properties, surface water and ground water controls, and stability considerations. They are suitable for any type of tailings and deposition method.

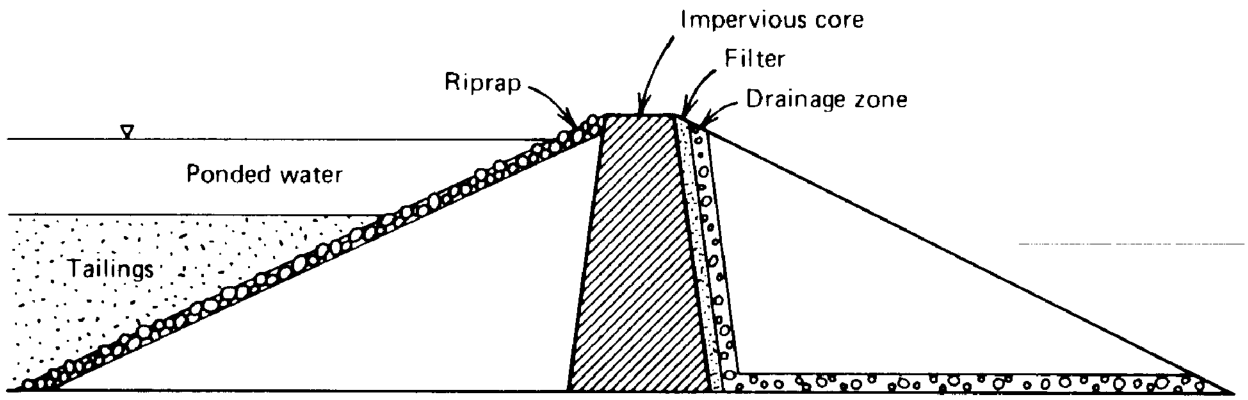

Figure 1. Water-Retention Type Dam for Tailings Disposal

(Source: Vick 1990)

Raised embankments can be constructed using upstream, downstream, or centerline methods, which are explained in more detail in a later section (see Figure 2). Each of the structures in Figure 2, for instance, is constructed in four successive lifts, with constructing material and fill capacity increasing incrementally with each successive lift. They have a lower initial capital cost than retention dams because fill material and placement costs are phased over the life of the impoundment. The choices available for construction material are increased because of the smaller quantities needed at any one time. For example, retention dams generally use natural soil whereas raised embankments can use natural soil, tailings, and waste rock in any combination. (Vick 1990)

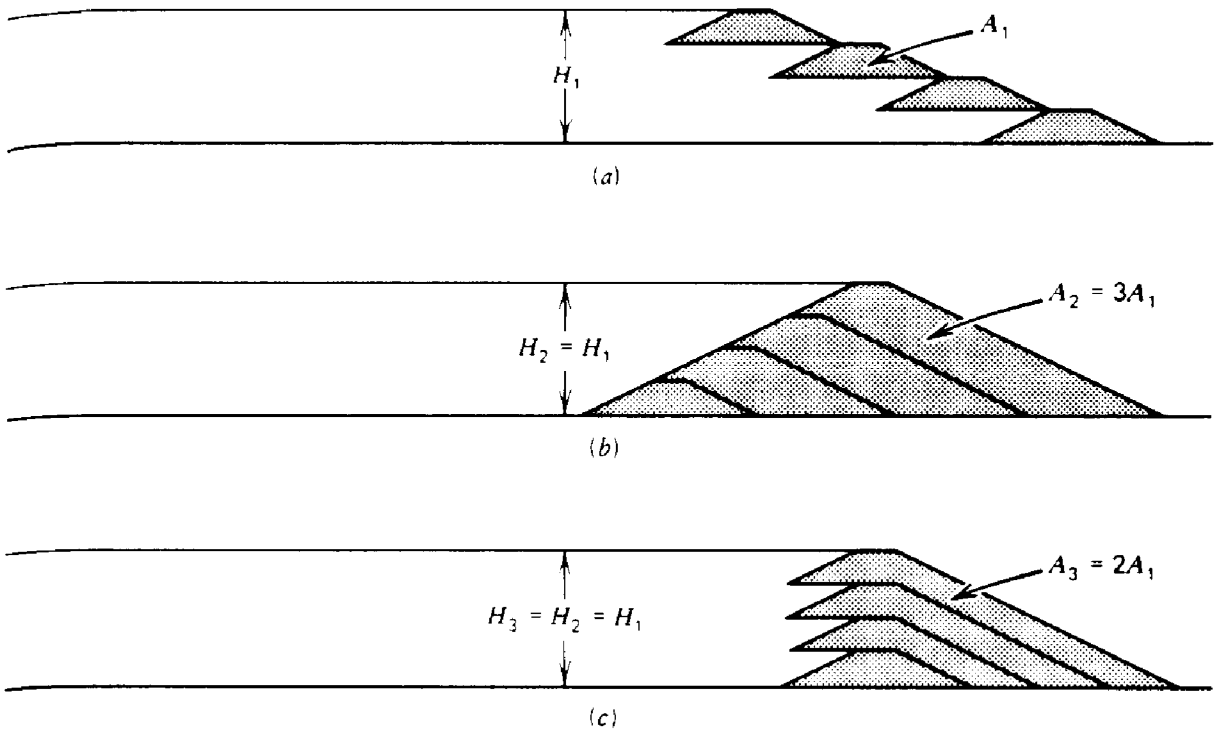

Figure 2. Embankment Types: (a) Upstream, (b) Centerline, (c) Downstream or Water Retention Type

(Source: Vick 1990)

Finally, the phased nature of raised embankments makes it possible to attempt to address problems that may arise during the life of a tailings impoundment. For example, at the Rain facility in Nevada, unplanned seepage under and through the base of the tailings embankment made design changes necessary. The fact that this was a raised embankment made it possible to attempt engineered solutions to the problem as the dam was enlarged and raised during later phases of construction, and this could be accomplished without taking the impoundment out of service and without moving enormous quantities of fill material or impounded tailings.

2.2.1 Valley Impoundments

Other things being equal, it is economically advantageous to use natural depressions to contain tailings. Among other advantages are reduced dam size, since the sides of the valley or other depression serve to contain tailings. In addition, tailings in valleys or other natural depressions present less relief for air dispersion of tailings material. As a result, valley impoundments (and variations) are the most commonly used. Valley-type impoundments can be constructed singly, in which the tailings are contained behind a single dam or embankment; or in multiple form, in which case a series of embankments contain the tailings in connected "stair-step" impoundments.

There are several variations of valley-type impoundments. The Cross-Valley design is frequently used because it can be applied to almost any topographical depression in either single or multiple form. Laid out similarly to a conventional water-storage dam, the dam is constructed connecting two valley walls, confining the tailings in the natural valley topography. This configuration requires the least fill material and consequently is favored for economic reasons. The impoundment is best located near the head of the drainage basin to minimize flood inflows. Side hill diversion ditches may be used to reduce normal runon if topography allows, but large flood runoff may be handled by dam storage capacity, spillways, or separate water-control dams located upstream of the impoundment. Figure 3 shows single and multiple cross-valley impoundment configurations.

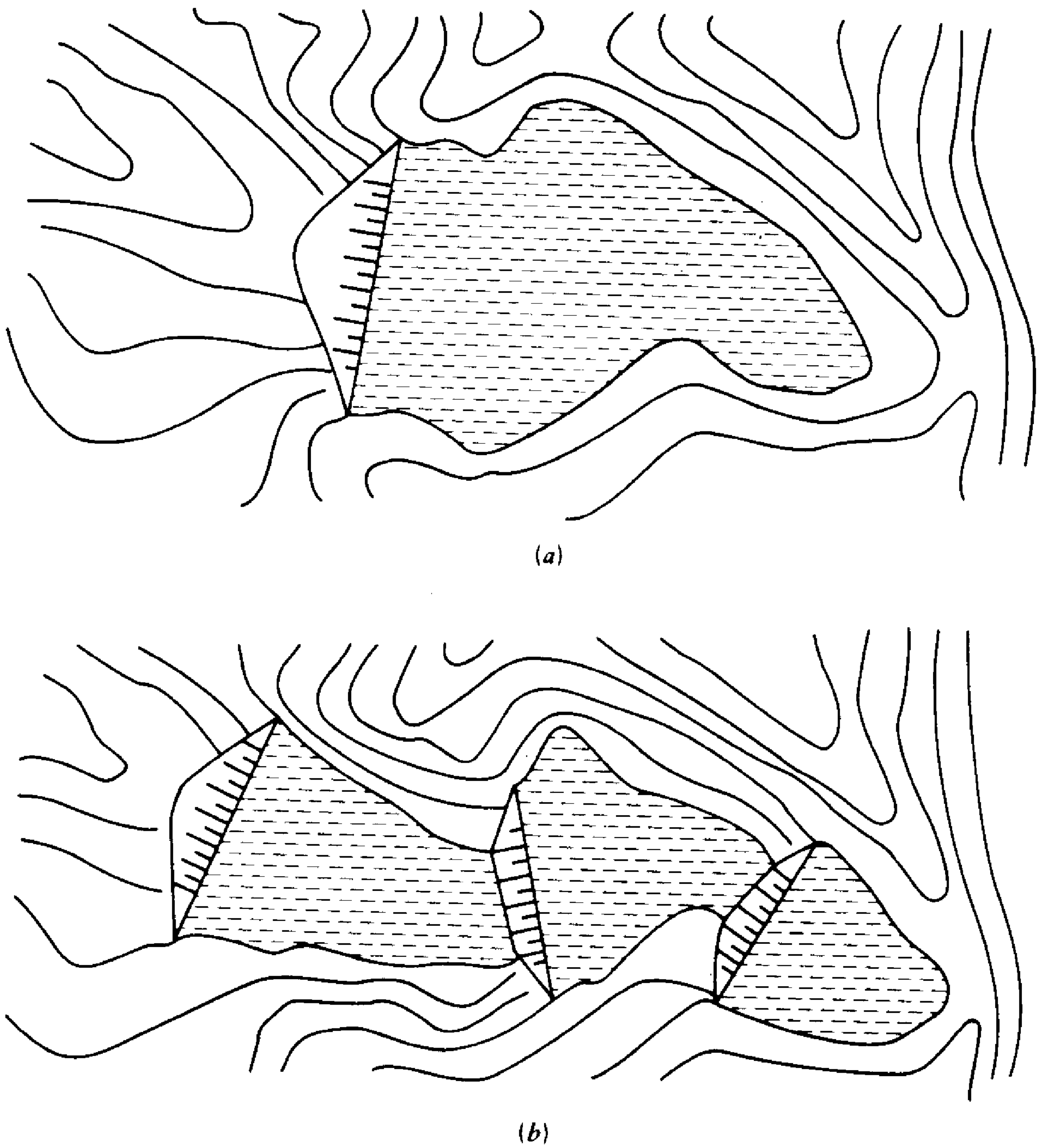

Figure 3. Single (a) and Multiple (b) Cross-Valley Impoundments

(Source: Vick 1990)

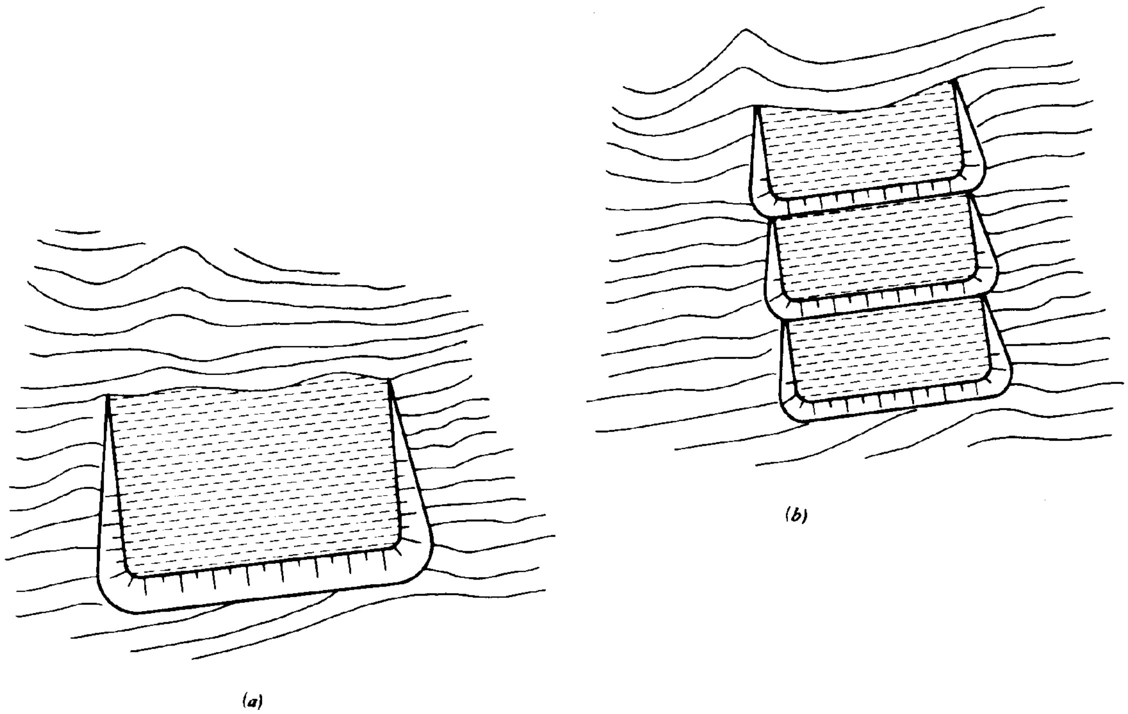

Figure 4. Single (a) and Multiple (b) Side-Hill Impoundments

(Source: Vick 1990)

Other types of valley impoundments may be employed when there is an excessively large drainage catchment area and/or there is a lack of necessary valley topography. Two variations are the side-hill impoundment and the valley-bottom impoundment. The side-hill layout consists of a three-sided dam constructed against a hillside (Figure 4). This design is optimal for slopes of less than 10% grade. Construction on steeper slopes requires much more fill volume to achieve sufficient storage volume (especially when using the downstream method of construction).

If the drainage catchment area is too large for a cross-valley dam and the slope of the terrain is too steep for a side-hill layout, then a combination of these two designs, the valley-bottom impoundment, may be considered (Figure 5). Valley-bottom impoundments are often laid out in multiple form as the valley floor rises, in order to achieve greater storage volume. Because the upstream catchment area is relatively large, it is often, or usually, necessary to convey upstream flows around (and/or under) valley-bottom impoundments.

The valley dam configurations are often the optimum choice for economic reasons. This is because the valley walls form one or more sides, so that the dam length is reduced, minimizing construction costs. However, decreased construction costs and low average depth of tailings in the embankment may be offset by increased environmental mitigation and increased costs of shut-down and reclamation.

The valley dam design is particularly sensitive to overtopping by flood waters, erosion near the intersection of the dam and the valley hillside, and liquefaction due to higher volumes of surface water inflow from drainages within the natural catchment basin and from high precipitation runon/runoff. As is described in more detail later, the stability of a valley dam depends largely on the level of hydrostatic pressure within fill material and the embankment. An unusual, one-time rise in the hydrostatic pressure above design levels may be sufficient to trigger failure. The control of inflows across, around, or under the impoundment is important to retaining structural stability and to controlling environmental impacts. Providing adequate internal drainage can help guard against liquefaction, and improve the permeability and consolidation of the tailings, thereby improving the stability of the structure.

Because a shorter embankment is required in this configuration, it is more feasible to consider impervious cores and internal drains as a means of controlling the phreatic surface and promoting stability of the embankment. Surface water controls may also be necessary. Diversion channels may not always be an option due to the difficulty of construction along steep valley sides. However, closed conduits may be an alternative diversion method. Another alternative surface water control in the valley layout is to construct a smaller water-retaining dam upstream of the tailings dam to collect the water to divert it around the tailings or use it in the mill. A water-related factor that also must be considered, particularly in valley impoundments, is the presence of shallow alluvial ground water. Ground water can infiltrate the tailings, thus raising the level of saturation within the tailings; this can be seasonal, in response to seasonal high surface water flows that interconnect with the alluvium upgradient of the impoundment (or under the impoundment itself).

It should be noted that any design that calls for diverting or otherwise controlling water flows during the active life of the impoundment has to consider later periods as well. The water balance may be more favorable after tailings slurry water is no longer being added to the impoundment/and the dam stability may be less of a concern. However, if there are toxic contaminants in the tailings, or if the tailings are reactive, the design must account for environmental performance following surface stabilization and reclamation.

The stability of the tailings impoundment is also dependent on (or at least related to) foundation characteristics, such as shear strength, compressibility, and permeability. Depending on soil characteristics, the valley layout can be adapted to account for high permeability materials in the design through the use of liners and/or adequate internal drainage. Soil characteristics often can be improved through soil compaction. In addition, the method of tailings deposition and construction have an increased impact on the valley impoundment layout. The deposition of tailings affects consolidation, permeability, strength and, subsequently, the stability of the embankment material. All these factors are discussed in later sections.

In some cases, liners or zones of low permeability may be appropriate means of controlling seepage to enhance stability or environmental performance. The upstream face of tailings dams/embankments (i.e., the side that contacts the tailings), for example, is frequently designed to provide a layer of low permeability or to be impermeable. The effect is to lower the phreatic surface through the embankment. This is usually accomplished with the slimes fraction of tailings and/or with synthetic materials.

Lining the entire impoundment area is more problematic, both because of the expense and because irregularities in valley side walls and floors make it difficult to ensure consistent liner integrity. Liners or layers of low permeability may be necessary, however, to impede flows to and from underlying ground water. More common than impermeable synthetic or clay liners is the practice of compacting native soil, including any available local clays, to reduce permeability to an acceptable level; dewatered or dried-in-place slimes may also be used in some cases. Should a liner or low-permeability layer be necessary, it must be designed to account for impoundment loadings, differential settlement, toxic or corrosive seepage, and weathering effects. If impoundments will desaturate after reclamation, for example, clay or slimes can crack and provide a pathway for ground water to enter the tailings or for contaminated seepage to enter ground water. Similarly, layers of clay or slimes that are prepared in anticipation of late impoundment expansion can develop cracks if they are allowed to dry before being covered with tailings.

2.2.2 Ring-Dike Impoundments

Where natural topographic depressions are not available, the Ring-Dike configuration may be appropriate (Figure 6). Instead of one large embankment (as in the valley design), embankments (or dikes) are required on all sides to contain the tailings. Construction can be similar to valley dams, with tailings, waste rock, and/or other native materials typically used in later phases of construction. Because of the length of the dike/dam, more materials are necessary for this configuration, and material for the initial surrounding dikes is typically excavated from the impoundment area.

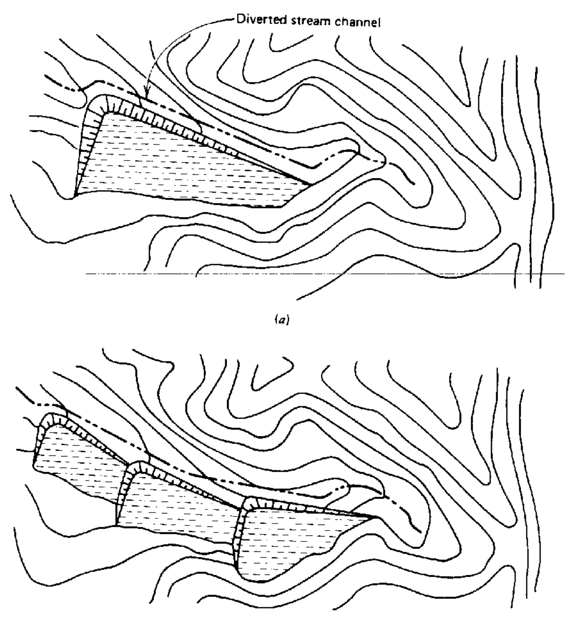

Figure 5. Single (a) and Multiple (b) Valley-Bottom Impoundments

(Source: Vick 1990)

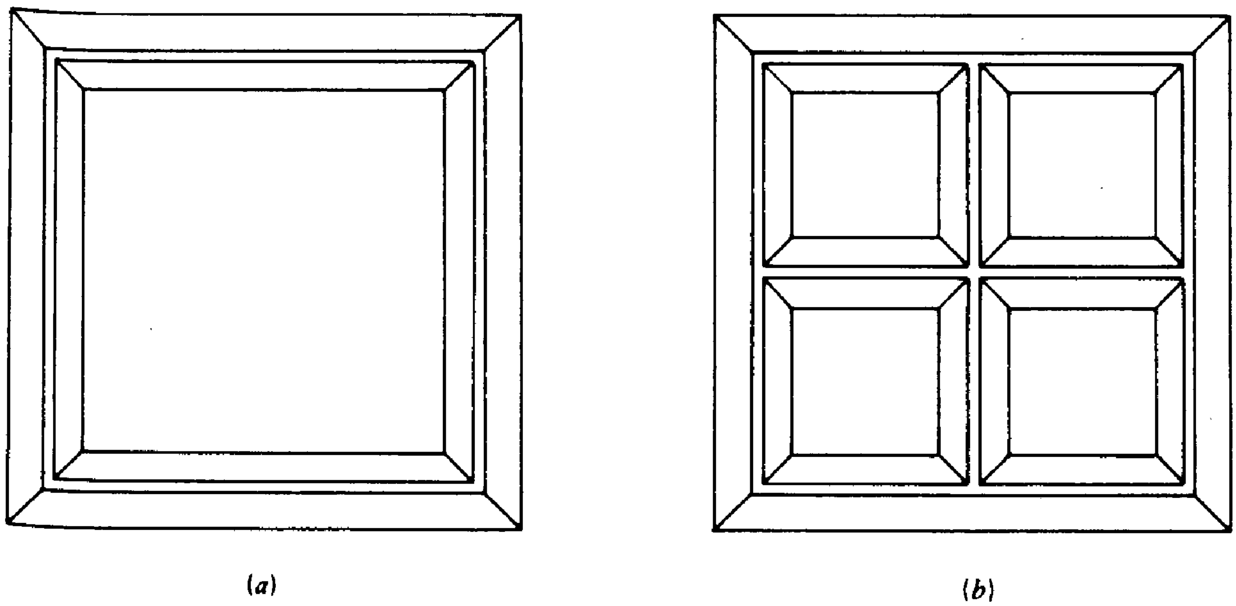

Figure 6. Single (a) and Segmented (b) Ring-Dike Impoundment Configurations

(Source: Vick 1990)

According to Ritcey (1989), most recent dike dams have been built using downstream or centerline methods rather than the upstream method (see below for descriptions of the various types of construction); Ritcey cites Green (1980) as reporting that long-term stability of upstream dikes is not certain.

Embankments are required on all sides, so this method utilizes a large amount of embankment fill in relation to the storage volume. This layout can be arranged in single or segmented form. The regular geometry typically used with this configuration makes it amenable to the installation of various kinds of liners. (Vick 1990)

If the terrain is flat and thus suitable for ring-dikes, this configuration allows maximum flexibility in actually selecting a site. Since the dikes are relatively low in height, the design is often simpler than a high valley dam design. Containment can be achieved by using an impervious core in the dikes and/or the use of a liner below the impoundment.

Unlike valley impoundments, which are located in a natural catchment area, the ring-dike design enables better maintenance of water control. The quantity of pond water is limited to that transported with the tailings and any precipitation falling directly onto the impoundment. There is no runoff other than from outer slopes. Since surface runoff and flood impacts are reduced, a smaller pond area and/or less elaborate water control measures are required. A trade-off can be made with a high tailings depth that reduces surface area and results in less seepage. There are also drawbacks to this design, including the relatively large volumes of material necessary for construction, and its effect on cost. The increased length of the embankment walls also may increase the possibility of failure (Robertson 1984, cited in Ritcey 1989). Other disadvantages of the ring dike system are that the impoundment rises above the surrounding terrain, creating an aesthetic problem in some locations, and there can be considerable wind erosion of the tailings. In many areas, also, there is no flat terrain suitable for ring-dike designs.

Although each situation needs to be evaluated on its own merits, the ring dike system has the potential for better control of seepage than that found in most valley dam locations. If warranted by the characteristics of a particular tailings, almost total containment and collection of effluent can be achieved using a suitable combination of low permeability cores, liners, and drainage system. Since seepage control is often a pressing environmental concern with tailings impoundments, the ring dike system can have an important advantage over most other layouts.

2.2.3 In-Pit Impoundments

This method is much less common than the valley and ring-dike impoundments. It consists of disposing tailings material into a previously mined pit. The design initially eliminates the need for dike construction.

Since the tailings are protected by pit walls, wind dispersion is minimized. Good drainage can be incorporated into the design. Many of the failure modes common to tailings embankments (e.g., piping, liquefaction) do not apply to this design. The lack of dam walls reduces the possibility of slope failure, but the stability of the pit slopes do have to be checked.

Unless the purpose is to isolate sulfide tailings underneath water, the water table should be below the tailings disposed in the pit. This may require backfilling with mine rock or overburden. If backfilling underneath the tailings is necessary, and/or if the surrounding rock is not sufficiently impermeable, a liner may be required. Ritcey (1989) notes that the hydrogeological parameters affecting the migration of seepage and contaminants are poorly understood, so tailings with toxic contaminants or reactive tailings may be poor candidates for this type of impoundment.

When mining in an active pit is proceeding laterally, the mined-out portion of the pit may be suitable for tailings disposal. In such cases, dikes would be constructed to impound the tailings in the mined-out area. This embankment could then be raised in a phased approach (Ritcey 1989).

2.2.4 Specially Dug Pit Impoundment Design

This design is fairly unusual and involves the excavation of a pit specifically for the purpose of tailings disposal. The impoundment consists of four or more cells with impermeable liners and surrounded by an abovegrade dam. Material removed from the pit is used in construction of the dam. This dug pit/dam design has some of the same advantages as the ring-dike design, including site independence and uniform shape.

Site independence benefits the design, since less effort and cost are needed to counteract topographic obstacles, soil conditions, climatic conditions, and construction obstacles. The uniform layout, shape, and flat terrain prevents surface runoff from entering the impoundment and decreases the requirements for flood control measures.

3. TAILINGS IMPOUNDMENT DESIGN

The actual design of a tailings dam and impoundment occurs only after the site has been selected. However, the site selection and design are best considered to be a dynamic process. A number of design principles should affect the site selection process as well as the determination of the embankment type and the impoundment configuration. This section first describes some of these fundamental design principles as well as major design variables and site-specific factors that influence ultimate design. As noted previously, the major considerations in the design of a tailings dam and impoundment are stability, cost, and environmental performance.

3.1 Basic Design Concepts

In general, tailings impoundments (and the embankments that confine them) are designed using information on tailings characteristics, available construction materials, site specific factors (such as topography, geology, hydrology and seismicity) and costs, with dynamic interplay between these factors influencing the location (or siting) and actual design of the impoundment. Because water is a major component in any tailings impoundment system, principles of hydrology (applied to flow of water through and around the tailings embankment) dictate many of the rules of tailings impoundment design. Indeed, because impoundment and dam stability are in large part a function of the water level, these principles are of fundamental concern in the design of any tailings impoundment.

One of the basic principles used in the design of impoundments and their embankments is the maintenance of the phreatic surface within the embankment. The phreatic surface is the level of saturation in the impoundment and embankment (the surface along which pressure in the fluid equals atmospheric pressure (CANMET 1977)); in natural systems it is often called the water table. The phreatic surface exerts a large degree of control over the stability of the embankment, under both static and seismic loading conditions (Vick 1990). The major design precept is that the phreatic surface should not emerge from the embankment and should be as low as possible near the embankment face (Vick 1990). This basically maintains a pore pressure at the face of the embankment lower than atmospheric pressure plus the weight of the embankment particles and maintains the face of the dam. Thus any factors that might affect the phreatic surface in the embankment may also affect stability of the embankment. The primary method of maintaining a low phreatic surface near the embankment face is to increase the relative permeability (or hydraulic conductivity, since water is the fluid) of the embankment in the direction of flow. (See Figure 7.)

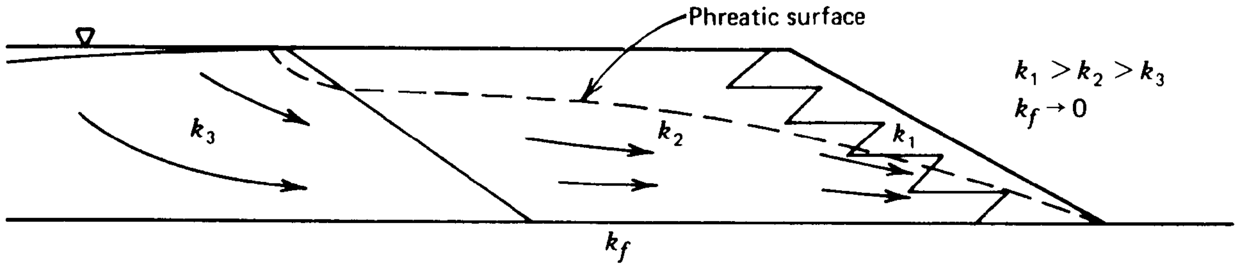

Figure 7. Phreatic Surface Through a Tailings Impoundment

(Source: CANMET 1977)

Creating a relative increase in permeability downstream can be accomplished in one of two ways, or a combination of the two: by incorporating lower permeability zones in the upstream areas of the embankment (typically by constructing embankments with low permeability cores) and by using higher permeability zones downstream (typically using internal drainage zones). The selection of which technique to use is often based on the availability of materials, such as clays for cores and/or clean sands for drains. The use of cores and drainage zones to maintain embankment stability are further discussed in a later section. It should be kept in mind, however, that major changes in phreatic surface require permeability differences in adjacent zones to be two or more orders of magnitude (Vick 1990).

The low permeability layer generally controls the overall flow rate through the impoundment. This allows higher permeability layers located downstream of the low permeability layer to drain and avoid increased pore pressure. The rule on increasing permeability in the direction of flow only applies in areas near the embankment face; if a low permeability core in the center of the embankment is used and permeability increases downstream toward the face, permeability of the material on the upstream side of the embankment may have little effect on the phreatic surface downstream of the low permeability core (Vick 1990).

In most embankments, materials in the various zones are also arranged to meet filter requirements, which are designed to prevent migration of tailings and finer materials into coarser zones. Otherwise voids will be produced that can form a pathway through the dam along which water can escape. As seepage rates accelerate along the pathway, erosion of the dam material occurs leading to failure of the dam. Such failures are referred to as piping failures, because of the natural "pipe" that is formed through the embankment. Piping failures can be avoided by the proper application of various filter rules that have been established in the design of water-retention dams. (Vick 1990)

Factors that affect the phreatic surface in the embankment affect its stability. These factors include the depositional characteristics of the tailings (permeability, compressibility, grading, pulp density, etc.) and site-specific features such as foundation characteristics and the hydrology and hydrogeology of the impoundment area and its upstream catchment area. Changes in the phreatic surface in a waste embankment will change the pore water pressures and consequently the resistance of the dam materials to sliding. Changes to the phreatic surface can be caused by: malfunction of drainage systems, freezing of surface layers on the downstream slope of the dam, changes in construction method (including the characteristics of the placed material), and changes in the elevation of the pond. The level of the water table also may be altered by changes in the permeability of the underlying foundation material; sometimes these are caused by strains induced by mining subsidence (Vick 1990).

In addition to maintaining the phreatic surface for stability purposes, dam design now includes factors related to environmental impacts associated with tailings seepage. By the use of liners, drains, and pumpback systems, tailings seepage may be controlled. These techniques are discussed in more detail in a later section of this report. The design should also address the future reclamation of the site.

3.2 Design Variables

3.2.1 Tailings-Specific Factors

Tailings composition, pulp density, grading, and other characteristics are used in the design of tailings impoundments in three basic ways: tailings analysis to assess the potential use of tailings sands in constructing the embankment, analysis of tailings to be placed in the impoundment to determine their potential impact on structural stability and seepage characteristics, and mineralogical analysis to determine the potential chemical aspects of seepage or other discharges from the impoundment. In addition to the physical characteristics, the method of deposition of tailings into the impoundment plays a role in the "engineering characteristics." (Vick 1990)

Tailings sands are often used as an inexpensive source of material for embankment construction; by removing the sands for embankment construction the volume of tailings to be disposed of is reduced. Depending on the gradation (grain size distribution) of the tailings, a cyclone may be used to separate sufficient amounts of coarse sand from the whole tailings to construct the embankment, leaving a higher percentage of slimes to be deposited behind the embankment. Cycloned sands can have both high effective strength and high permeability, the two major characteristics necessary for downstream embankment material. In addition, cycloning results in the deposit of the less permeable slimes behind the embankment, possibly reducing impoundment seepage.

With regard to their general physical properties, tailings are considered to be soils, subject to traditional soil mechanics patterns of behavior. Index properties (gradation, specific gravity, and plasticity) are determined by relatively simple tests that can be performed on tailings produced in bench testing of the mill process. These index tests are a guide to the engineering properties of the tailings. Caution is required, however, since tailings differ in subtle ways from soils having similar index properties (Vick 1990).

Tailings properties that impact design, stability and drainage of the impoundment include in-place and relative density, permeability, plasticity, compressibility, consolidation, shear strengths, and stress parameters (Vick 1990). In-place density is an important factor in determining the size of impoundment required for a specific operation while relative density influences dynamic strength behavior. In-place density refers to the mass/unit volume of an undisturbed sample of material where the sample volume is much greater than the average particle size. Gradation is a factor of in-place density, with well graded materials typically having a higher density (CANMET 1977). Permeability (or hydraulic conductivity) of tailings in-place in the tailings impoundment varies in both horizontal and vertical directions due to the layered way most tailings are deposited. Plasticity refers in a general way to the amount of clay present. More specifically, the Plasticity Index is the range of moisture content over which a soil is plastic; numerically, it is the difference between the Liquid Limit and the Plastic Limit of the soil. Tailings with a high Plasticity Index are finer-grained and have low permeability and drainage characteristics, while tailings with a low (or zero) Plasticity Index are more coarse and have high permeability drainage properties. Consolidation and compressibility are related to particle size (sands vs. slimes) and density or void ratio. These are a measure of the change in overall volume the tailings may experience over time with dewatering and/or added load. Tailing sands and slimes, for example, are more compressible than otherwise similar soils. Shear strengths and stress parameters of tailings are functions that affect stability and are impacted by pore pressure. The interaction of all of these factors is complex and affects the phreatic surface in impoundment and embankment. For more information, see Vick 1990; and CANMET 1977.

In addition to tailings characteristics that affect stability and seepage quantity, tailings can be analyzed to determine seepage water quality. Besides process chemicals (e.g., cyanide) that may be present, metal mine tailings may contain an array of minerals originally present in the host rock that can contaminate tailings seepage. Contaminants including arsenic, copper, lead, manganese, selenium and other metals. Tailings also can have significant levels of radioactivity.

Tailings and effluent may be acidic or caustic, and in some cases are neutral but later become acidic. The oxidation of sulphides, particularly pyrite (FeS) and pyrrhotite ($Fe_{1-x}S$: Fe_6S_7 to $Fe_{11}S_{12}$) can result in the generation of acid drainage. In the presence of free oxygen, the pyrite oxidizes to produce acidic conditions. The chemical reaction is the combination of metal sulfide and water to produce a metal hydroxide and sulfuric acid. In addition to chemical oxidation, a bacterium (thiobacillus ferrooxidans) causes bacterial oxidation which may become the dominant process in the later stages of acid production. The acidification of tailings ponds can occur in tailings that were initially alkaline; as water levels drop within the tailings impoundment, they introduce air into the void spaces and the subsequent oxidation produces acids. Analysis of the ore and tailings prior to disposal is useful in anticipating water quality problems and the need to adjust seepage flows. Water management and the associated fate and transport of contaminants is addressed in a later section.

3.2.2 Site-Specific Factors

Site-specific factors play a major role in the design of an impoundment. Siting considerations include: (1) physical considerations such as volume of tailings and area required by the dam, (2) financial considerations such as the amount and cost of fill material, water controls, and tailings depositional methods, and (3) environmental requirements such as flood control, ground water and surface water contamination, and wildlife habitats.

The process of selecting the most favorable site typically is a screening process wherein less suitable sites are successively removed from further consideration. The screening criteria include cost, design constraints, and environmental conditions/performance; the importance of each of the criteria may vary depending on the operation and the site being screened. In selecting an appropriate site, the constraints are imposed mainly by the mill location, topography, hydrology, geology, and hydrogeology (Vick 1990). Consideration of all potential factors and full investigation of the potential site can alleviate design problems once a site has been selected. Because design factors also influence site selection, a dynamic iterative process of site selection can result in the most favorable outcome.

Mill Location

Tailings are generally transported from the mill in slurry form, typically with a solids content from 15 to 55 percent by weight. This requires an extensive piping system for the tailings, as well as for pumping reclaim water back to the mill. Vick (1990) quotes an average cost of about $500,000/mile for these systems. Consequently, sites close to the mill are favored on a cost basis over those further away. Initial site screening usually considers sites within about five miles of the mill; this distance may be expanded later if no suitable sites are found. Ideally, sites are located downhill from the mill to allow gravity flow of the tailings to the impoundment and to minimize slurry pumping costs; however, pipelines with steep gradients are avoided where possible. Sites having small elevation rises from mill to impoundment may not be ruled out.

Topography

In addition to distance and elevation, natural topography is one of the main considerations for the given impoundment volume required. The aim is to achieve maximum storage capacity with the least amount of embankment fill. Natural valleys and other topographical depressions are usually investigated first. As a rule of thumb, embankment heights are kept below 200 feet. High embankments (greater than 400 ft) often pose design and construction problems that could be avoided by better siting. (Vick 1990) Topography is also an important factor in the site's hydrology.

Hydrology

Surface water hydrology factors generally favor water diversion around the impoundment and the minimization of water inflows into the impoundment (unless one of the objectives is to collect water for the mill operation). In general, these flows are minimized both for normal and flood conditions. If possible, this is achieved by locating the impoundment as close as possible to the head of the drainage basin to minimize the costs of constructing surface water diversion structures. In order to avoid excessive water handling requirements, the total catchment area should be less than 5 to 10 times the impoundment surface area (Vick 1990). Even then, there must be provisions for controlling runon and runoff after the impoundment is "closed."

Because location, topography, and hydrologic considerations and constraints are relatively easily evaluated, they assume great importance in the screening process. As site investigations proceed (and more costly investigations are necessary), it may be appropriate to re-examine some sites that are eliminated from further consideration early in the process.

Geology and Ground Water

Once the site screening criteria of mill location, topography, and hydrology have been applied, the number of siting options usually has been considerably reduced. Geologic considerations then assume a critical role. In particular, site geology affects the foundation of the embankment, seepage rates, and the availability of borrow materials for embankment construction. Soft foundations, for example, may limit the allowable rate of embankment build-up in order to allow for adequate pore pressure dissipation. Sloping foundations and the presence of weak layers in the foundation will need to be investigated since they may contribute to slope failure of the embankment.

Although geologic details are critical to siting and design, they often play a secondary role in actual siting decisions. This is because there are usually a limited number of sites available at this stage (the rest having been eliminated by consideration of mill location, topography and hydrology). In addition, the lack of detailed information often precludes any meaningful comparisons of alternative sites. The tendency is to try to engineer around any geologic problems. If, following the site investigation, a "fatal" geologic problem is discovered, the site will have to be abandoned at that time. The search will then continue for one or more suitable sites.

Ground water conditions are usually related to the geology, and also affect siting conditions. A high water table limits the amount of dry borrow material available for construction, and shortens the distance for seepage to enter the ground water system. In addition, shallow ground water can infiltrate tailings and increase the amount of water in the impoundment.

Initially, various observations and assessments can assess broad geologic factors, including the availability of construction materials, special construction problems with respect to nearby structures, drainage conditions at the site, and apparent ground stability of the site (such as slumping, evidence of weak planes within the rock, faulting, etc.). The type of vegetation present can indicate subsoil characteristics. Test pits and trenches may be dug and test holes may be drilled to obtain soil and/or rock samples. *In situ* permeability tests also may be run in holes drilled at the site of the proposed tailings impoundment area.

A proposed site will undergo a geotechnical site investigation. The investigation will assess site geology, including the depth, thickness, continuity, and composition of the strata; site hydrogeology; geotechnical properties of soil and rock affecting design; and availability of suitable construction materials for building dams, dikes, drains, and impervious liners.

Geotechnical testing on soils is generally undertaken to determine water content, grain-size distribution, Atterberg limits (moisture content in soil as measured in the boundary stages of four states of soil: liquid, plastic, semi-solid, and solid), consolidation, shear, permeability, and ion exchange capacity (of clays considered for liners). For rocks it is usually necessary to know the shear strength along weak layers, and the permeability and strength of the various strata.

These tests are usually performed in combination with *in situ* tests such as standard penetration, static cone, vane shear, and pressure meter, in order to obtain useful data on field properties. While estimates of soil permeability may be determined in the laboratory, these values need to be confirmed through field testing, which may include borehole *in situ* methods, and large scale pumping methods. In addition, ground water measurements, including piezometric pressures in the underlying soil/sand rocks, and water sampling are usually undertaken to establish baseline conditions prior to construction of the impoundment.

Foundations

The foundation area beneath the embankment is assessed using the geotechnical and other methods noted above. Weak material beneath the slope, such as buried slopes once exposed to weathering, snow covered surfaces over which additional material has been deposited, layers of fine material included in a coarse material embankment, and foundation strata of low shear strength, can cause rotational sliding. If a deposit of clay is extensively fissured, water penetrating into the fissures can seriously weaken the deposit due to the dependency of the shear strength on the softened material strength adjacent to the fissures. Compression or consolidation of the foundation can cause appreciable settling of the overlying material, sometimes causing cracks in tailings embankments (or zones of embankments) that can lead to seepage or piping.

The permeability of the foundation significantly affects the stability of an embankment. When an embankment is constructed on a foundation of saturated impervious clay, for example, the loading of the embankment will create excess pore water pressure in the foundation material. Because the immediate loading is taken by the water phase in the foundation material, there is no increase in shear strength and the rapid increase in loading can precipitate embankment failures extending through the foundation. If the foundation material beneath the tailings dam is pervious, excessive seepage can lead to piping failure. All of these foundation factors are taken into account during design.

Seismicity

The design of tailings impoundments usually has to consider potential seismic activity at the site. This requires the selection of a design earthquake for the site in question. A method commonly used to determine the effects of the design earthquake on a particular site is to assume that the earthquake occurs on the closest known possibly active fault. The fault is selected on the basis of the geological studies previously conducted in the area. Attenuation tables are then used to estimate the magnitude of the earthquake forces reaching the site as a result of the design earthquake occurring on the selected fault.

4. EMBANKMENT CONSTRUCTION, STABILITY, AND FAILURE

4.1 Embankment Construction

Tailings embankment design investigations, described above, lead to the selection and refinement of a starter dam that will serve as the starting point for embankment construction. The starter dam design specifies the internal and external geometry of the structure, and should include specifications for drainage, seepage control, and in some cases liner systems required to maintain embankment stability and control releases to the environment. It is important to emphasize that final embankment design may differ substantially from initial expectations. If embankment construction continues throughout the active life of the impoundment, experience gained from ongoing monitoring and analysis allow for changes and improvements in the design to better meet project goals.

In general, if the starter dam design includes liners and/or drainage systems, such systems must be developed prior to or concurrently with initial dam construction, as well as with each successive raise of the embankment. Environmental considerations may create a need for liners since tailings may have a potential to leach toxic or undesirable constituents to underlying strata; similarly, it is desirable to limit the flow of shallow ground water into the tailings. Liners may be composed of compacted native soils, compacted tailings slimes, imported or local clays, synthetic materials, gunite, etc. For economic reasons, compaction of native soils or tailings slimes are the preferred methods of reducing the permeability of impoundment bases where these methods will meet objectives. Further, as a practical matter, some impoundment designs, such as cross-valley impoundments, may not be amenable to any other type of liner; with very large surface areas and uneven terrain, the use of synthetic liners or other imported materials is generally prohibitively expensive for this type of impoundment, even if it is technically feasible.

Drainage systems may be required for structural reasons. As discussed above, a primary concern accompanying the use of tailings for embankment construction is the control of pore water pressure within and beneath the embankment. Excessive pore pressure within the embankment may lead to exceedence of the sheer strength of the fill material, resulting in local or general slope failure. Additionally, high pore pressures within or beneath the embankment face may result in uncontrolled seepage at the dam face leading to piping failure (discussed below). Similarly, seepage through weak permeable layers of the foundation may result in piping or exceedence of soil shear strength, causing foundation subsidence and compromising the stability of the overlying embankment. These and other threats to embankment stability may be partially reduced through seepage control. Generally speaking, seepage control may be affected through the establishment of zones of differing permeability up-stream of, beneath, and within the embankment, either through drainage systems or low permeability layers or cores, or both.

The primary function of drainage systems is the dissipation of pore pressure across the embankment. Drainage systems allow the control of the phreatic surface by providing low-pressure conduits for seepage. A number of methods are available to accomplish this goal. In particular, chimney drains and blanket drains, each composed of materials of permeability at least two orders of magnitude greater than that of the embankment fill itself (Vick 1990), may be installed within and beneath the embankment to allow dissipation of pore pressure. Chimney drains are vertical curtains of high permeability material, while blanket drains are horizontal layers of high permeability material. Variations of each may be used depending on design requirements. The location of such drainage zones depends on the method of construction of the embankment, discussed below.

Critical to the performance of drainage systems is the prevention of clogging; this can occur, for instance, when tailings fines infiltrate the drainage zone. Filters or filter zones may be employed to help prevent clogging and hence maintain differences in permeability across zones. Filter zones may be constructed of graded sands or synthetic filter fabrics (Vick 1990).

The foregoing discussion underscores an important concept common to tailings impoundments in general: seepage through tailings embankments is essentially unavoidable and often necessary. Since the purpose of the tailings embankment is to impound tailings slurry (and allow for reclamation of mill process water), and since tailings sands used for construction of the embankment are never impermeable, hydraulic head across the embankment will never be zero. Some water will migrate through and/or under the embankment.

4.2 Construction Methods

A variety of construction methods and materials are used in the construction of tailings embankments. In general, mines choose materials and methods to provide the required stability at the lowest cost. If the tailings dam is near the mine, the use of waste rock can significantly lower the cost of materials, while also reducing the need for waste rock disposal areas. If borrow materials are to be used, they can be obtained from the impoundment area and increase impoundment capacity. The materials also should meet permeability, compressibility and shear strength requirements. They also must be chemically stable, so potentially acid-generating waste rock is not suitable for embankment construction, particular in drainage systems. The most frequently used material in embankment construction is tailings.

4.2.1 Construction Using Tailings Material

The use of tailings material is generally the most economical construction method. As discussed previously, some of the disadvantages of using tailings as dam-building material include: high susceptibility to internal piping, highly erodible surfaces, and high susceptibility of the fine tailings to frost action. Also, loose and saturated tailings are subject to liquefaction under earthquake shocks. During construction of the tailings dam, the two major ways to improve these qualities are use of coarse fractions of tailings and compaction. Generally, the sand fractions, after being separated from the slimes, may be easy to compact using vibratory compactors. By compacting this coarse fraction of the tailings, the end result is a dense mass of strong material that has greatly increased resistance to liquefaction. Tailings separation most commonly occurs by spigotting or cycloning. The three methods of construction using tailings are upstream, downstream and centerline. A comparison of these methods is presented in Table 1.

Table 1. Comparison of Embankment Types

Embankment Type	Mill Tailings Requirements	Discharge Requirements	Water-Storage Suitability	Seismic Resistance	Raising Rate Restrictions	Embankment Fill Requirements	Relative Embankment Cost	Use of Low Permeability Cores
Water retention	Suitable for any type of tailings	Any discharge procedure suitable	Good	Good	Entire embankment constructed initially	Natural soil borrow	High	Possible
Upstream	At least 60% sand in whole tailings. Low pulp density for grain-size segregation.	Peripheral discharge, well-controlled beach necessary	Not suitable for significant water storage	Poor in high seismic areas	Less than 15-30 ft/yr most desirable. Over 50 ft/yr can be hazardous	Native soil, sand tailings, waste rock	Low	Not possible
Downstream	Suitable for any type of tailings	Varies according to design detail	Good	Good	None	Sand tailings, waste rock, native soils	High	Possible (inclined cone)
Centerline	Sands or low-plasticity slimes	Peripheral discharge of at least nominal beach necessary	Not recommended for permanent storage. Temporary flood storage can be designed.	Acceptable	Height restrictions for individuals raises may apply	Sand tailings, waste rock, native soil	Moderate	Possible (Central cone)

(Source: Vick 1990)

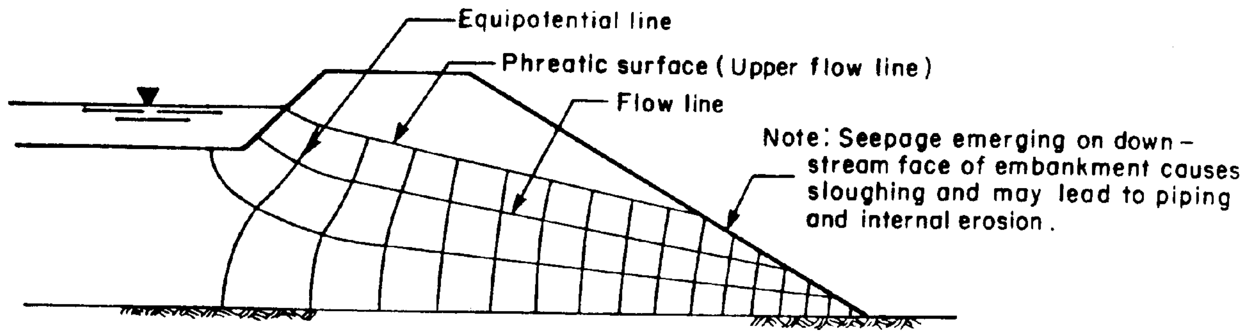

Figure 8. Upstream Tailings Embankment Construction

(Source: Vick 1990)

4.2.2 Upstream Method

Upstream construction, the oldest and most economical method, begins with a starter dam constructed at the downstream toe (Figure 8). The starter dam should be capable of passing seepage water and the downstream portion should be resistant to piping. The tailings are discharged peripherally from the crest of the starter dam using spigots or cyclones. This deposition develops a dike and wide beach area composed of coarse material. The beach becomes the foundation of the next dike. In some applications, the dikes are mechanically placed and the discharge is used to build the beach only (in addition, slimes may be used to coat the upstream face of the dike to reduce permeability). These dikes can be built with borrow fill, or beach sand tailings can be excavated from the beach and placed by either dragline or bulldozer. Either way, some type of mechanical compaction of the dike is typically conducted before the next stage of the dam is constructed.

The single most important criteria for the application of the upstream construction method is that the tailings beach must form a competent foundation for the support of the next dike. Vick (1990) states that as a general rule, the discharge should contain no less than 40 to 60 percent sand. This can preclude the use of the upstream method for those mill tailings that contain very low percentages of sand. Other references state that the determining factor for upstream versus downstream construction is grain-size distribution of the tailings. In addition to grain size tests, Brawner, et al, (1973) suggested that, "If a tractor cannot be operated on the first 100 to 200 feet of beach, the grind is too fine for upstream construction methods."

In addition to tailings gradation, several other factors can limit the applicability of this method. These factors include phreatic surface control, water storage capacity, seismic liquefaction susceptibility and the rate of dam raising. Upstream embankment construction offers few structural measures for control of the phreatic surface within the embankment. Vick (1990) identified four important factors influencing the phreatic surface location: permeability of the foundation relative to the tailings, the degree of grain-size segregation and lateral permeability variation within the deposit, and the location of ponded water relative to the embankment crest. Only the pond location can be controlled through operational practices. The other factors must be planned for in the construction design phase. Both proper decanting and spigotting procedures can be used to control the distance between the pond's edge and the embankment crest. Although the pond's location can be controlled to some extent during operation, a tailings pond that is expected to receive high rates of water accumulation (due to climatic and topographic conditions) should be constructed using a method other than upstream construction. Any change in environmental or operating conditions (heavy rainfall, blockage of seepage outlets, rise in water levels of the pond, etc.) resulting in a rise of the phreatic line and complete saturation of the outer sand shell could quickly lead to failure by piping or sliding. An outer rockfill shell may mitigate failure potential from piping or sliding.

Tailings embankments constructed using the upstream method generally have a low relative density with a high water saturation. This combination can result in liquefaction of the tailings embankment in the event of seismic activity. In addition, vibration of sufficient intensity and magnitude caused by blasting, trains, heavy trucks, etc., may cause liquefaction. The shear strength can be reduced to near zero such that the fluidized slimes easily burst through the remaining thin, unsaturated sand-dike shell and the dam collapses and flows. This can occur at very low heights and slope angles. Therefore, upstream construction is not appropriate in areas with a potential for high seismic activity.

The rate of embankment raises is limited by the build-up of excess pore pressures within the deposit. This build-up of pore pressures can lead to a shear failure, which may result in breaching of the dam and the release of contained tailings (Brawner 1973). The height at which potential failures are triggered depends on the strength of the tailings within the zone of shearing, the downstream slope of the dam, and the location of the phreatic line.

Horizontal drainage zones may be installed during starter dike construction to help maintain low pore pressure within the embankment. Vick (1990) states that a blanket drain extending well upstream of the starter dike may be effective in lowering the phreatic surface in the initial and subsequent embankment rises. He notes, however, that special effort must taken to ensure against blockage of blanket drains when used in upstream embankments.

4.2.3 Downstream Method

The design requirements for the downstream method of construction are similar to conventional water storage dams. As in upstream construction, downstream construction also begins with a starter dam constructed of compacted borrow materials, however, this starter dam may be constructed of pervious sands and gravels or with predominately silts and clays to minimize seepage through the dam (Figure 9). If low permeability materials are used in the starter dike, internal drains will need to be incorporated in the design. The downstream method is so named because subsequent stages of dike construction are supported on top of the downstream slope of the previous section, shifting the centerline of the top of the dam downstream as the dam stages are progressively raised.

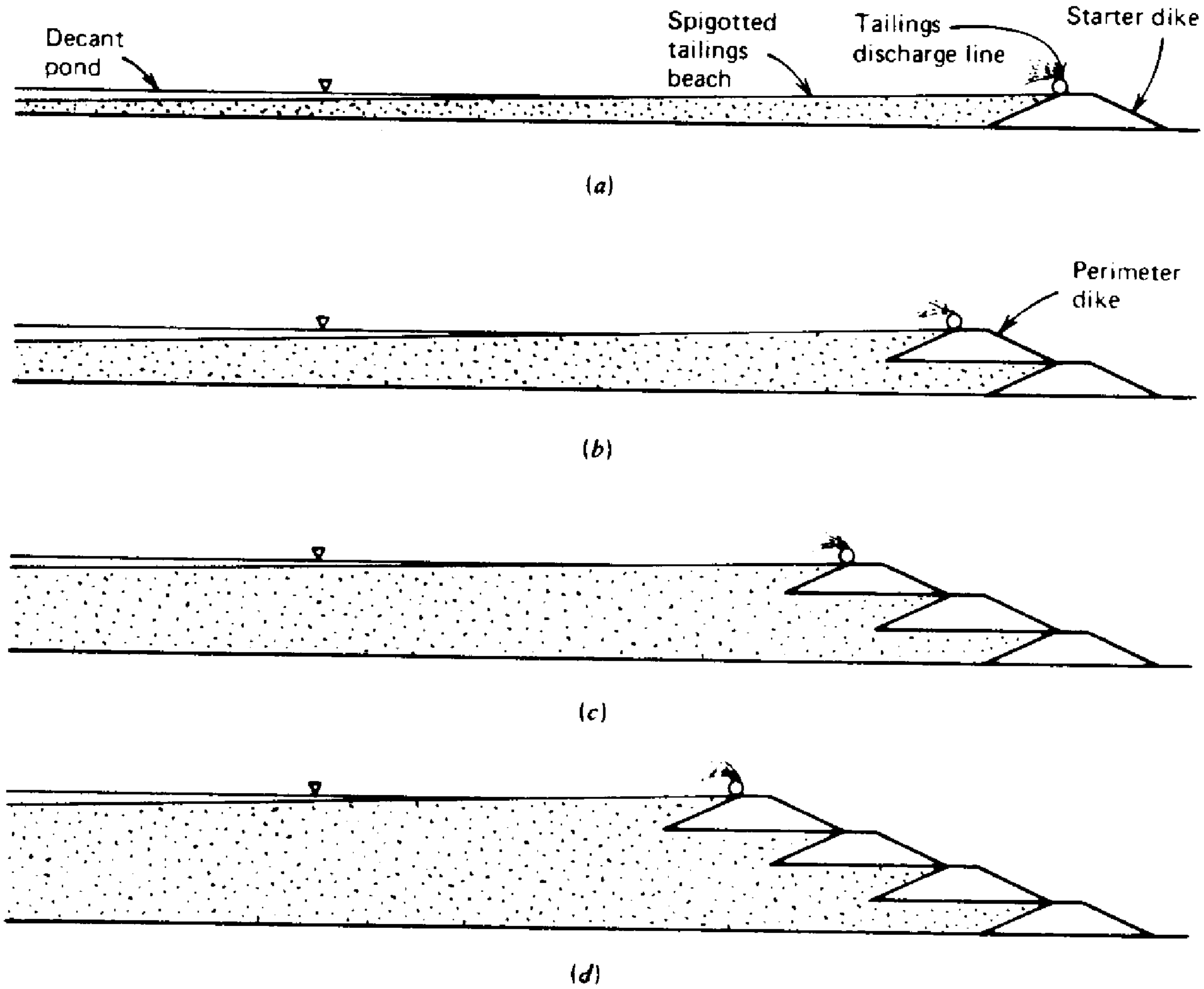

Figure 9. Downstream Embankment Construction

(Source: Vick 1990)

A variety of tailings depositional techniques can be used in conjunction with the downstream construction method, but peripheral spigotting of tailings is very common. Coarse tailings can be spread in thin layers utilizing on-dam cycloning, or they can be hauled from a central cycloned stockpile, then spread and compacted. If the volume of coarse tailings is not sufficient to construct the dam, local borrow materials may be incorporated for part of the structure. If coarse rock is used, due to its porosity, a filter or impervious upstream membrane is required to prevent piping of the tailings through the rock. If spigotting is controlled to create a wide tailings beach and the embankment has been made of permeable tailings, the phreatic surface may be controlled without the need for internal impervious zones or drains. However, Brawner, et al. (1973) recommend that if the dam will be constructed in a potential earthquake zone and/or its height is to exceed 50 ft, the downstream extensions must be compacted to a higher relative density than is typical to minimize the risk of liquefaction.

The downstream construction method allows for the incorporation of drains and impervious cores to control the phreatic surface. Brawner, et al. (1973) recommended the placement of a pervious sand underdrain layer or alternative drainage system prior to each downstream extension. Several other drain designs can also be incorporated into the design. For example, an inclined chimney drain near the upstream face of the dike, and connected to a blanket drain at the dikes base, may be installed with each successive raise of the embankment. (Vick 1990) Drainage controls help to control the phreatic surface and minimize the chance for build-up of pore water pressures which reduce shear strength. Due to the ability to incorporate drains into the design, this method of construction is well-suited to conditions where large volumes of water may be stored along with the tailings solids.

The downstream method of construction provides a degree of stability not found in upstream construction due to the ability and ease of compaction, the incorporation of phreatic surface control measures and the fact that the dam raises are not structurally dependent upon the tailings deposits for foundation strength. A major disadvantage of this method is the large volume of fill material required to raise the dam. The increased volume of fill required can dramatically increase the cost of this method of construction if the tailings from the mill cannot provide a sufficient volume of sand. Embankments constructed with downstream raises also cover a relatively large area, which can be a major disadvantage if available space is limited.

4.2.4 Centerline Method

Centerline construction is similar to both the upstream and downstream construction methods in that the embankment begins with a starter dam and tailings are spigotted off the crest of the dam to form a beach. The centerline of the embankment is maintained as fill and progressive raises are placed on both the beach and downstream face (Figure 10). The tailings placed on the downstream slope should be compacted to prevent shear failure. The centerline method of construction provides some of the advantages over the other two methods while mitigating some of the disadvantages.

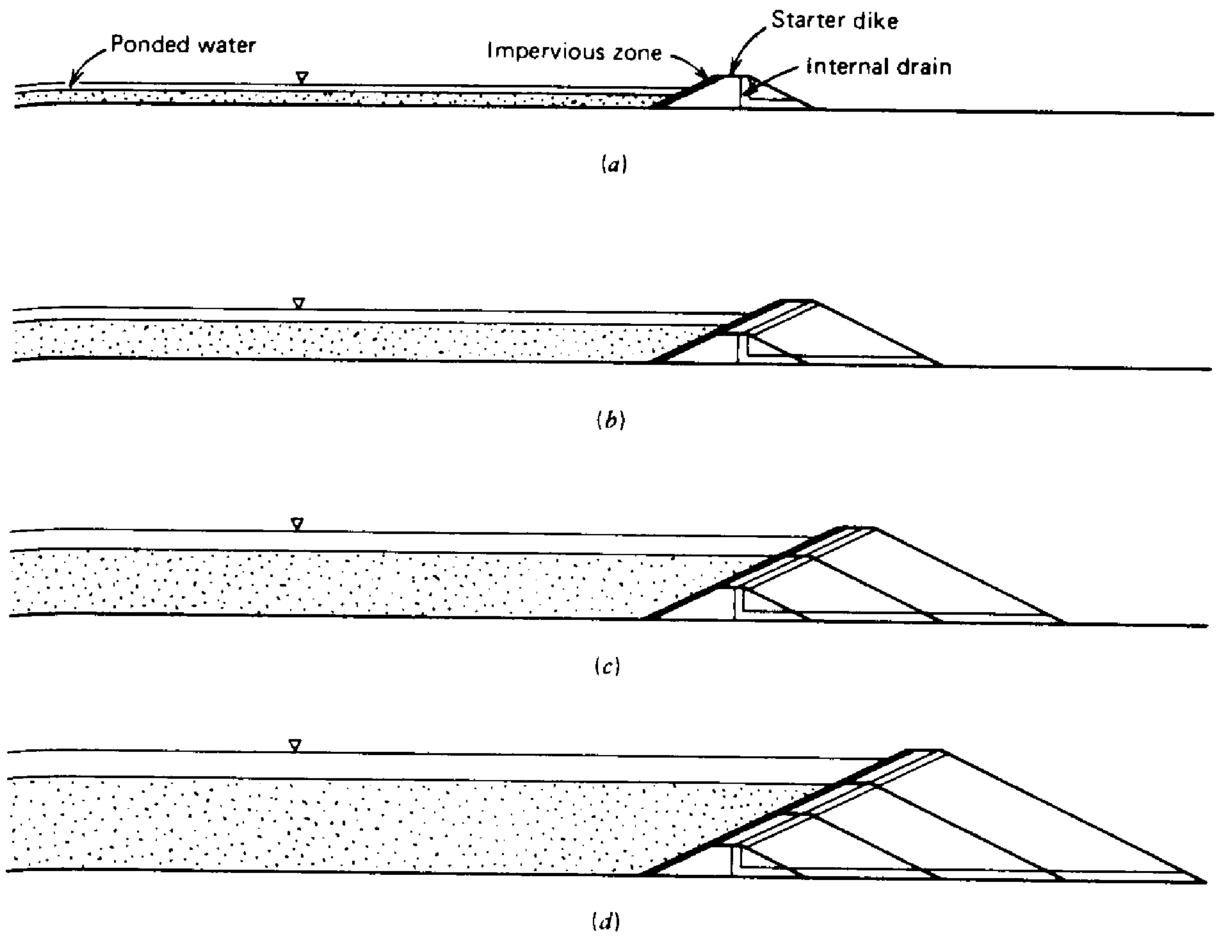

Figure 10. Centerline Embankment Construction

(Source: Vick 1990)

As in the downstream method, drainage zones can be incorporated into the construction. A wide beach is not mandatory and this method is amenable for use with tailings that contain a relatively low percentage of sand. Since less sand is required, the dam raises may be added faster than in the upstream or downstream methods. Coarse gradation of the tailings is necessary if rapid drainage is required to provide support for construction equipment.

Although this embankment type is not amenable to permanent storage of large volumes of water, short term storage of water due to heavy precipitation events or mill shutdown will not adversely affect the stability of the dam.

If the embankment has been properly compacted and good internal drainage is provided, this embankment type is resistant to seismic activity. Even in the event that the slimes placed against the upstream slope liquefy, the central and downstream portions of the dam may remain stable due to their good compaction and drainage characteristics.

4.2.5 Embankments Constructed Using Alternative Materials

Although the three embankment construction methods discussed above are typically built with large volumes of coarse tailings, portions of the dams (particularly the starter dam) may incorporate a variety of borrow fill materials. For example, waste rock and overburden excavated during open-pit stripping can be used to construct embankments. However, waste removed from the mine may not keep pace with the demand to raise the dam crest. Also, waste rock that may potentially be acid-forming is not suitable for embankment (or drainage) construction.

In general, where natural materials are used exclusively for dam construction, standard earth dam (water retention) design may be followed. A water retention dam constructed with native materials should contain internal zoning such as an impervious core, drainage zones, and appropriate filters. These designs are best suited when large volumes of water are planned to be stored with the tailings. Design changes are required to account for the higher unit weight of saturated tailings. In addition, since water retention dams are designed to limit the drainage through the core, placement of spigotted slimes on the upstream face usually produce a moderately impervious upstream seal.

4.3 Tailings Deposition

Generally, tailings slurry is transported through pipelines from the mill to the tailings impoundment for deposition. Once the tailings reach the impoundment, a variety of options may be employed to deposit the tailings. In determining which method is best suited for a particular operation, tailings engineers (generally civil engineers specializing in the disposal of mine tailings) study the characteristics of the tailings materials, the deposition cycle, and the climate. They will also consider the impoundment layout and the embankment design. In the discussion that follows, it is assumed that the embankment is not of the water-retention type, and that the tailings will be used to provide most of the material for construction of the embankment.

Three general methods of tailings deposition are typically recognized: single point discharge, spigotting, and cycloning. There are variations on all these methods and the methods may be used in combination to meet the design criteria set by the tailings engineers.

4.3.1 Single Point Discharge

Single point discharge is the technique of discharging tailings from the open end of a tailings pipeline. This method is often employed at impoundments that discharge tailings slurry upstream of the pond and dam (i.e., not from the crest of the dam). This technique is not appropriate when the pond (and/or the fine fraction of the tailings) must be kept well away from the embankment. Single point discharge can also be used to discharge slurry into the dam, but this requires that the discharge point be periodically moved to another section of the dam to prevent unequal raising of the dam sections. Further, the low surface area to volume ratio afforded by single point discharge makes this method attractive in extremely cold environments, where freezing of smaller discharge streams may occur (Lighthall 1989).

4.3.2 Spigotting

Spigotting is the technique of discharging tailings through small pipes (spigots) that originate from multiple points at regular intervals along a tailings header line (Lighthall 1989). The method is used to achieve a more or less uniform flow of tailings, which in theory, will create uniform beaches. However, the location of the discharge points may require rotation to create these uniform beaches. Spiggotting forms a gently sloping beach where the coarsest fraction settles near the point of discharge and the fine fraction (slimes) is deposited progressively farther away from the discharge points. As a result of this variable gradation, the density, shear strength, and permeability of the settled solids decrease with increasing distance from the discharge point. As discussed above, these distributional characteristic could be very favorable in reducing the phreatic surface before and across the embankment. However, observations of actual particle size, permeability, and shear strength distribution with distance from the point of discharge suggest that the smooth ideal gradation theoretically achievable may be rarely achieved in practice (Vick 1990, Lighthall 1989). Nevertheless, consideration of the header tailings velocity, the solids concentration in the header and spigot lines, and the point of discharge (among other factors) may allow the development of beaches which provide structural stability to the main embankment while also creating a long seepage path (providing consequent dissipation of pore pressure) from the pond to the embankment (Lighthall 1989).

4.3.3 Cycloning

Tailings sands (the coarse fraction of the tailings) may be used to construct tailings dams during active deposition. Mining companies typically view cost savings as the major advantage of using the coarse fraction in this manner. Since the sand is produced from the material to be deposited (the tailings), any costs related to acquiring borrow fill for the construction of embankments is eliminated or significantly reduced. This practice also reduces the overall volume of tailings to be deposited in the impoundment, since at least part of the coarse fraction has been used in the dam construction. The method used to separate the fines from the coarse fraction in the total tailings slurry is cycloning.

Cyclones are simple mechanical devices used to separate coarse and fine particles from a slurry through centrifugal action. As the slurry, moving under pressure, enters the cyclone, the fine particles and most of the water rise to the top outlet. The coarse particles spiral downward through a conical section and exit the bottom. The separated fine fraction is referred to as overflow and the sand fraction is known as the underflow. It is the underflow that is used to construct the tailings embankments, while the overflow is discharged through a separate slimes pipeline to the impoundment itself. The underflow and overflow should be monitored regularly to measure pulp densities, gradation, and cyclone inlet pressures. Adjustments of the cyclones are routinely required to maintain pulp density and grain size objectives.

Certain criteria should be considered when evaluating whether cycloning can be an effective tool in the construction of a tailings embankment. The cycloned sands should have a permeability that is sufficiently higher than the slimes deposited in the impoundment such that the phreatic surface can be adequately controlled in the dam. The sands should also allow quick drainage upon discharge to ease handling and spreading of the sands. The volume of the cycloned sand recovered from the whole tailings must be great enough to allow for dam raises as needed to maintain adequate volume in the impoundment for slimes. If the volume of cycloned sand falls short of the amount needed for dam raises, costs could increase as borrow materials are required to maintain adequate impoundment volume. Tailings that contain less than 60 percent particles passing the number 200 sieve are generally considered to contain acceptable sand quality for use in cycloning. Two-stage cycloning, employing two cyclones in series, is often used to produce a sand fraction that contains less fines than single-stage cycloning.

Two basic methods of cycloning are in common use for tailings dam construction: central cycloning (or stationary cycloning) and on-dam cycloning. A third method, hydraulic cell cycloning, is a more sophisticated application that is less commonly used. The central cycloning method establishes a single permanent or semi-permanent high capacity cyclone at a strategic location, often on a dam abutment higher in elevation than the projected dam crest. The cyclone underflow creates a tailings sand stockpile for use in embankment construction while the overflow from the cyclone is discharged to the center of the impoundment. Earth-moving equipment moves the tailings sand from the stockpile to the embankment where they dump and compact it. The mechanical placement and compaction results in sands with a high relative density. Therefore, the method is well suited for use in areas susceptible to seismic activity.

The on-dam cycloning system consists of several cyclone units set up on towers, skids, trucks, scaffolds or suspended from cranes established along the dam crest. The number of cyclones is determined by the size of the cyclones and the mill throughput. The underflow sand from the cyclones is deposited on the embankment face while the overflow is discharged to the impoundment. The high pulp density underflow (typically 70 to 75 percent solids) results in the deposition of steep-sided sand piles at a slope of 3:1 to 4:1 (horizontal to vertical) on the slope of the embankment that is under construction. The cyclones are moved as the sand cones raise the height of the embankment. Normally the grade of sand placed by the cyclones does not vary with distance from the discharge point. However, this may differ between sites: Lighthall, et al. (1989) reported that if high pulp density underflows are used, tailings operators may sometimes lower the pulp density of the underflow to wash out the cones rather than move the cyclones too frequently. This practice could result in not meeting the grain size objective for the face of the embankment.

The on-dam cycloning system is cost-effective since the sands are placed in their final resting place hydraulically and no mechanical action is necessary. One disadvantage of this method is that the nonmechanical placement results in lower relative densities, ranging generally from 30 to 68 percent as reported in Lighthall, et al. (1989). Although relative densities between 45 and 50 percent can normally be achieved, relative densities below 30 percent are not uncommon. These low relative densities may eliminate this method of deposition from use in areas of high seismic activity.

The hydraulic cell method deposits diluted cyclone underflow (i.e., sands) into bermed cells on a tailings embankment. The tailings are cycloned at a central cyclone and the water is added to the underflow to ease pipeline transport to the cells on the embankment. The solids in the cells are then allowed to settle before the excess water is decanted from the end of the cell opposite the point of discharge. Some mines use wide-track bulldozers to compact the sands in the cells during deposition. Lighthall, et al. (1989) and Mittal and Hardy (1977) report that relative densities in excess of 60 percent can be achieved with the hydraulic cell method and mechanical compaction. Without mechanical compaction, Lighthall, et al. (1989) and Mittal and Morgenstern (1977) report that relative densities of tailings in excess of 50 percent can be achieved.

A major advantage of the hydraulic cell method is the achievement of high relative densities using direct hydraulic deposition (and possibly mechanical compaction). The method presents limitations for use on narrow embankments since a relatively wide, flat embankment area is required for cell construction. Furthermore, fines should be limited to 5 to 10 percent in the cyclone underflow to achieve highly permeable sands that allow quick drainage of water in the cell. This limitation of the fines component in the underflow may result in reductions in total overall sand recovery and, hence, the reduction in sand available for dam construction.

4.4 Stability Analysis

From initial trial embankment design to final site closure, the stability of the tailings embankment remains an important consideration. The primary objective of the impoundment engineer is to develop a reliable waste containment structure at the lowest possible cost. Choices regarding materials, slope angles, drainage control, raising rates, etc., all affect the cost as well as the stability of the structure. Therefore, stability analysis is performed to optimize the structure with respect to cost and other objectives while maintaining reliability.

Slope stability analysis begins with an estimation of the reliability of the trial embankment. Typically, the embankment designer proposes the internal and external geometry of the trial embankment and then calculates the safety factor of the design. Using detailed information on the physical properties of the fill material and estimates of the volume of tailings and water to be contained in the impoundment, the phreatic surface is predicted. The designer then examines a wide range of failure modes (discussed below) to calculate the estimated stresses expressed at hypothetical failure surfaces. The safety factor for each failure mode is then calculated by dividing the estimated resistance of the embankment to stress along the failure surface by the stress load expressed at the failure surface. With this process the designer can look at changes in design parameters and the resulting influence of the safety factor to arrive at the least-cost option consistent with safety objectives (Inyang 1993).

Once impoundment construction has begun, the quality of information available for slope stability analysis improves. The above process may be repeated for each raise of the embankment, replacing estimates of phreatic surface levels and the physical properties of fill materials with measured values collected in the field

(Mittal and Morgenstern 1974). Based on additional safety factor calculations, embankment design may be changed significantly before the structure is completed.

There are numerous methods for performing slope stability analysis. However, a more detailed discussion of these methods is beyond the scope of this paper. Vick (1990) and CANMET (1977), among others, provide much more detailed discussions. The following is a brief discussion of flow nets, used to determine seepage flow characteristics within an embankment.

4.4.1 Flow Net Analysis

In conducting stability analysis, flow nets can be used to estimate seepage direction and volume and pore pressure at points within the embankment (CANMET 1977). A flow net is a graphical solution of Darcy's law to show steady flow through porous media and is often used to show ground water flow. The variables include flow characteristics (either in terms of flow or head), information on the boundaries of the area to be modeled, and information on the hydraulic conductivity within the area. Boundary conditions are the characteristics of flow at the edges of the system being modelled[1].

In a flow net, a grid is formed by the intersection of flow lines (the path that an individual particle of water flows through a region) and equipotential lines (representing contours of head) (Freeze and Cherry 1979). According to Vick (1990), for most types of embankments, flow nets provide conservative estimates of pore pressures within the embankment, with static pore pressure at a point being roughly equal to its depth below the phreatic surface.

In working with seepage and pore pressures, understanding of some basic definitions in terms of hydraulic conductivity or permeability are necessary. Homogeneous means that hydraulic conductivity (K) (or the coefficient of permeability) in the material (natural soil or the embankment) is independent of position. Isotropic means that hydraulic conductivity is independent of direction at the point of measurement. If hydraulic conductivity is dependent on position then the media is heterogenous. If hydraulic conductivity of a media is dependent on direction at the point of measurement then the media is anisotropic.

In generating a flow net, certain assumptions are made to solve the equation, including that the flow is steady state rather than transient (Freeze and Cherry 1979). For this reason, the use of flow nets to determine exact volumes of seepage may not be accurate due to the often transient and unsaturated flow conditions at most tailings impoundments (Vick 1990).

In homogeneous isotropic systems, (systems where hydraulic conductivity is the same throughout the media in terms of location and direction) flow lines and equipotential lines intersect at right angles, providing the graphical solution to Darcy's Law.

[1]Boundary conditions for a homogeneous isotropic media may be zero flow (an impermeable boundary), constant flow (constant head boundary) or a water table (where head approximates atmospheric pressure).

If the media is homogeneous and anisotropic, the cross section (prior to the addition of flow lines) can be converted to an isotropic system by a ratio of the vertical and horizontal conductivities[2]; the construction the flow lines is then conducted perpendicular to the equipotential lines, as with true isotropic systems. After the flow net is constructed, it can be transformed back into the original anisotropic system. (Freeze and Cherry 1979, CANMET 1977) For heterogeneous flow systems, a flow net can be constructed by sketching the different layers of hydraulic conductivity and by refracting flow and equipotential lines as they cross from one layer to another[3]. Also, the same volume that exits one layer must enter the next layer. Typically, layers with higher hydraulic conductivity have relatively horizontal flow lines compared to layers of lower hydraulic conductivity with relatively vertical flow lines. (Freeze and Cherry 1979, CANMET 1977)

Flow nets are generally effective for downstream and centerline dams, which generally mimic homogeneous systems. See Figure 11 for examples of typical flow nets for embankments under various conditions. Due to complex permeability variations (complex heterogeneity) and boundary conditions, flow nets are not always realistic for upstream embankments. Finite-element and other analysis can be used (Vick 1990). For additional information on the construction and use of flow nets, see CANMET 1977, Vick 1990, and Freeze and Cherry 1979.

[2]Convert by the square root of the hydraulic conductivity in the vertical direction by the hydraulic conductivity in the horizontal direction.

[3]The tangent law is used; See Freeze and Cherry 1979.

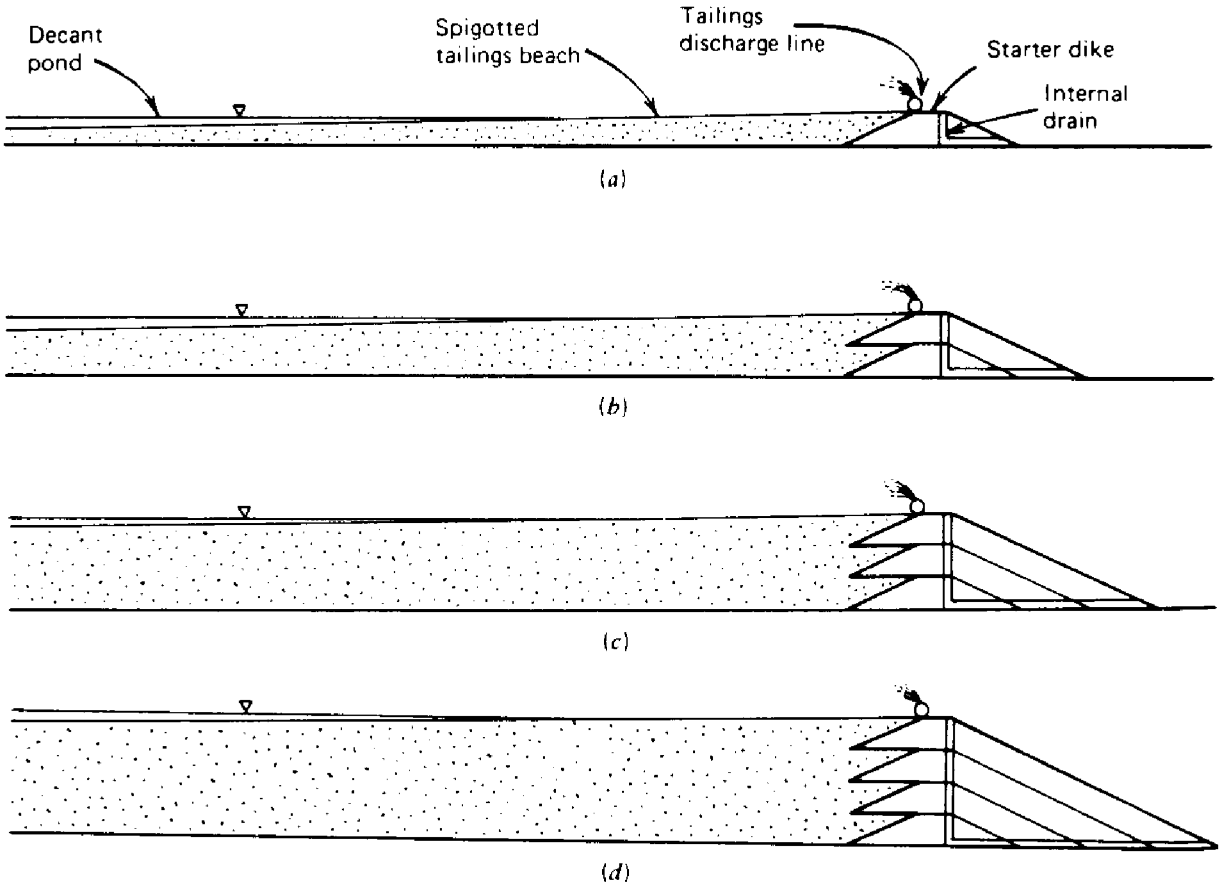

Figure 11. Examples of Tailings Embankment Flow Nets

(Source: CANMET 1977)

4.5 Failure Modes

As noted above, calculation of the safety factor for a tailings embankment requires an analysis of the potential failure surfaces of the embankment. There are a number of common failure modes to which embankments may be vulnerable. These include slope failure from rotational slide, overtopping, foundation failure, erosion, piping, and liquefaction. Each failure mode may result in partial or complete embankment failure.

4.5.1 Rotational Sliding

Rotational sliding, so named because the failure surface appears as a segment of a horizontal cylinder, may result in slope failures ranging from local sloughing of tailings at random areas along the face of an embankment to massive circular arc slides extending over the entire structure. In general, for a stable slope, the shear strength resisting movement along a potential failure surface exceeds the shear stress tending to induce movement. Instability occurs when the shear stress on the failure surface equals the shear strength

(Vick 1990). Specifically, causes of rotational failure may include changes in the water table, changes in the permeability of the foundation materials, disturbances to the embankment caused by vibration or impact loading, settlement of the foundation materials, etc (CANMET 1977).

4.5.2 Foundation Failure

Foundation failures are not uncommon among earthfill structures. Where a weak layer of soil or rock exists at shallow depth in the foundation below the structure, movement along a failure plane will occur if the earthfill loading produces stresses in excess of the shear strength of the soil in the weak layer (CANMET 1977).

4.5.3 Overtopping

One of the most common causes of failure is overtopping by flood waters. Overtopping typically results when the volume of run-on entering an impoundment, from improper diversion of surface water flows or excessive stormwater flow, exceeds the capacity of the impoundment. Because tailings embankments are constructed of highly erodible materials, the friction caused by rapid flow over an unprotected embankment crest may quickly erode a gully in the fill material, allowing sustained release to occur. Additionally, a rapid increase in pore pressure associated with large stormwater inflow may result in the liquefaction of unconsolidated impounded sands and slimes. Sustained high flow over the crest of an embankment can thus result in a major failure of the overall impoundment within minutes (CANMET 1977).

4.5.4 Erosion

In areas of heavy rainfall, some form of protection against erosion is usually required. Tailings embankments may be susceptible to erosion failure in two major areas, embankment abutments and the embankment face. Erosion along the contact line between the embankment and the abutment may result from stormwater flow that concentrates there (CANMET 1977). Typically, this type of failure is preventable with proper stormwater diversion methods and so results from faulty design or maintenance. Erosion of embankment faces may result from rupture in tailings lines installed on the embankment crest. Again, maintenance (and alternate siting of tailings lines) may prevent this type of failure.

4.5.5 Piping

Piping refers to subsurface erosion along a seepage pathway within or beneath an embankment which results in the formation of a low-pressure conduit allowing concentrated flow. Piping may result from seepage exiting the face of an embankment with sufficient velocity to erode the embankment face. The resulting void space promotes progressive erosion extending upstream toward the source of the seepage. In the worst case, the seepage may result in the creation of a direct channel from the tailings pond to the dam face (CANMET 1977). Excessive piping may result in local or general failure of the embankment or the embankment foundation.

4.5.6 Liquefaction

Liquefaction is one of the most common failure modes of cross-valley dams. Because tailings deposits typically comprise unconsolidated, saturated deposits of similarly-sized grains, they are susceptible to temporary suspension in water (Vick 1990). Liquified tailings may behave like a viscous fluid, such that they may pass through narrow openings and flow considerable distances (CANMET 1977). Accordingly, even small dam failures may result in substantial releases of impounded materials if those materials become suspended.

Factors affecting liquefaction potential include:

- *Soil type* - Uniform grain size materials, mostly in the fine sand sizes (the typical gradation of a tailings material), are the most susceptible to liquefaction.

- *Relative density or compactness* - For a given material, the more compact or dense it is the more resistant it will be to liquefaction.

- *Initial confining pressure at the time subjected to dynamic stress* - This offers an opportunity in certain areas to prevent liquefaction by applying overloads to loose deposits.

- *Intensity and duration of the ground shaking* - Liquefaction may occur due to an intensive earthquake, or due to prolonged earth movement.

- *Location of the water table* - A high water able is detrimental. Consequently, a tailings deposit constructed on a pervious foundation or a dam with a phreatic line kept low by providing adequate internal drainage features may have a greatly reduced potential for liquefaction. (Vick 1977)

By incorporating drainage facilities, maintaining a low pond surface, and compacting the fill materials during construction, the density, saturation, and confining pressures can be controlled to reduce the likelihood of liquefaction. If the tailings embankment is constructed of fine sands, compaction of these sands will increase their density and reduce their susceptibility to liquefaction. Compaction to obtain relative densities of 60% or greater provides reasonable protection (CANMET 1977). Therefore, provided embankment materials possess a relative density of 60% or greater, or provided the phreatic surface is maintained at a position well below the embankment surface, the embankment can have a sufficient factor of safety against liquefaction failure. Design calculations generally are needed to verify this for each individual dam.

4.6 Performance Monitoring

Routine monitoring and preventive maintenance are crucial in order to assure good performance of tailings impoundments. Monitoring can consist of visual observation of the tailings embankment, monitoring of piezometers and other instrumentation. Preventive maintenance, based on the early observation of potential "trouble spots," can maintain the stability of the structure, control seepage, and contain costs. Distress signals such as cracking, wet spots on the downstream face, and critical settlement, all indicate deficiencies in the structure, but without proper instrumentation it may be difficult to accurately interpret the extent of the problem. Piezometers, pressure gages, and inclinometers can be used to show developing trends in the behavior of the deposited materials. The observations made from these instruments, combined with disposal operation logs which show dates and locations of deposition, meteorological conditions, etc., can help analyze the situation. (Vick 1990)

Instrumentation should be installed in the embankment or its foundation to monitor changes which may be critical to stability, and in order to help predict unstable conditions. Instruments can be installed to measure pore water pressures, seepage flows, embankment movements, and total pressures.

Pore water pressure in soils may be measured with piezometers. The Casagrande piezometer, a simple and effective piezometer, has a porous ceramic stone element and is designed to measure pressure changes with a minimum lag time. It is installed in a hole drilled into the embankment or its foundation, and water levels are measured by a probe lowered down the hole. Similar types can be installed using porous plastic, porous bronze, perforated steel casing, or steel casing and well points. Hydraulic and electrical piezometers are also available and can be installed at various levels in an embankment. These piezometers are generally more complicated to operate, and their reliability over long periods requires great care in fabrication and installation. When encountered, seepage flow emerging downstream from the embankment, can be collected and directed to a weir for flow measurements. Records of seepage flow will indicate when significant changes occur and permit an evaluation of potential problems from piping.

Simple methods for measuring embankment movements can be utilized. Markers can be installed on the surface aligned in a straight line-of-sight to permit rapid detection of horizontal movement during periodic surveys. Successive measurements between two pegs spaced either side of a crack will indicate any widening and acceleration in separation rate. A more advanced device for measuring horizontal movement is the slope-indicator. For this device, telescoping cylindrical casing is installed in the embankment during construction. The sensing element is lowered down grooves inside the casing and measures the slope of the casing in two directions at right angles. From the measured slopes, the horizontal movements occurring over the length of the casing can be calculated. Surface settling can be measured through the use of leveling or temporary benchmarks.

The frequency of monitoring will depend on previous observations and the critical nature of the parameters. In most instances, frequent observations during and immediately after completing construction phase is important. When records indicate that conditions are relatively stable, frequency of observations can be extended. In some instances, measurements may be needed only after the occurrence of unusual conditions such as heavy surface runoff, peak floods, or seismic activity.

The characteristics of the tailings and the construction method may change substantially over the years taken to construct the dam. These changes can alter the conditions governing the stability of the embankment. Changes may take place in crest levels, water levels, embankment slopes, cross-section geometry, seepage conditions, and material characteristics. A continuous program of inspection and maintenance is necessary from the beginning of deposition throughout the life of the dam. Through careful monitoring, areas of concern may be noted and quickly repaired, thereby preventing failure. In addition to monitoring the stability of the dam, the performance of liners and drainage systems can be evaluated. Monitoring wells are useful in monitoring seepage.

5. WATER CONTROL AND MANAGEMENT

As discussed throughout this paper, the ultimate purpose of a tailings impoundment is to contain tailings in a cost-effective manner that provides for long-term stability of the impoundment and long-term protection of the environment. Water control and management are perhaps the most critical components of tailings impoundment designs and operation. The failure modes discussed previously are all related to water in the impoundment and/or the embankment. Similarly, the environmental impacts of tailings and impoundments are related to water control and management, either directly, as in the cases of ground or surface water contamination, or indirectly, as in the case of airborne transport of dry tailings. Water has been discussed in the previous section in terms of stability; in this section, it is discussed in terms of environmental performance. Most recently, environmental issues have come to the forefront of tailings impoundment design, with special concerns over the quality of effluent and seepage from tailings impoundments, both to ground water and surface water. This concern has lead to both an increase in treatment of especially toxic tailings effluent prior to discharge and more effort toward total containment of the tailings water within the impoundment. The latter effort (i.e., containment) is a challenge that has not been overcome: according to Vick (1990), some methods of seepage control are more effective than others; however, "`Zero discharge,' even with the use of impoundment liners, remains an elusive goal."

5.1 Surface Water

Control of surface water is one of the major factors involved in design and operation of a tailings impoundment. A mass balance approach to water management can be used, with variables categorized into outflows and inflows. Outflows from a tailings impoundment include overflows, evaporation, recycle and re-use, and seepage. Overflows are dependent on the dam's storage capacity and the runoff volume of a storm event in the basin. Evaporation rates are a function of the climate and the surface area of the freewater pond and saturated tailings. Recycling and re-use volumes depend on the operation's capacities and needs. Seepage can exit the dam as ground water or seepage through or under the embankment. This section describes the surface components of water flow into and out of the impoundment. Subsurface flows are described in a later section. Both surface and subsurface components interact in a dynamic fashion and must be considered together in any analysis.

5.1.1 Surface Water Evaluation

Estimation of surface water inflows and outflows using a mass balance approach includes both natural and man-made components. Variables include precipitation (including storm events), evaporation, run-on (including flood events), the liquid component of the tailings as it is discharged to the impoundment, water returned to the impoundment from any downstream seepage return systems, evaporation, infiltration, decanting and recycling tailings water, and any direct discharge (overflow). Ferguson et al. (1985) also include discharge to the free water pond resulting from tailings consolidation.

Precipitation data, topographic maps, streamflow measurements, and snow-depth data are used during impoundment design to prepare hydrographs and frequency curves for use in estimating volumes of precipitation and runon anticipated. Hydrographs, used for ultimate flood designs, determine changes in inflow rates and maximum flow rates. They illustrate stream discharge versus time for storms of various intensities and durations. Hydrographs are composed of interflow, surface water runoff, and baseflow (flow attributed to shallow ground water). Factors affecting hydrograph shape and height are rainfall intensity, distribution and duration; basin size, shape and drainage pattern (e.g. dendritic or trellis); and vegetation patterns.

Peak inflow rates are affected by rainfall intensity and are indicated on a hydrograph as the crest. Rainfall intensity is indicated by the slope of the rising limb. The direct runoff area is the area under the hydrograph minus the baseflow. The baseflow is indicated at the point where the hydrograph changes slope (inflection points).

Frequency curves, used for return-period flood designs, allow the designer to determine discharge rates of a design storm. Snowpack depth is incorporated into dam designs in areas with large snowfalls or fast snowmelts. Avalanche frequencies in the area are considered in the design as appropriate. Rules of thumb are that freshly-fallen snow has a water content of 10 percent while spring and compacted snow have a water content of 30 percent by volume. The importance of containing seasonal rapid snowmelt is worth emphasizing. The Bureau of Mines states that lack of sufficient snowmelt capacity is believed to be one of the major factors responsible for the Summitville leach pad failure, and tailing ponds are similarly vulnerable.

Modelling and analysis can be used estimate the volumes of naturally occurring inflows and outflows, such as precipitation and evaporation. Methods for estimating some of the major naturally occurring inflows and outflows are summarized below; additional inflows and outflows, which have an element of human control, are described in the water controls section.

Storm Events

Runoff volumes can be calculated through precipitation, discharge, and vegetative data of the area. Precipitation data from wet and dry years are used to provide minimum, average, and maximum runoff volumes for determining storage capacity and control structures for the dam. Calculations generally include a time continuum because the dam surface area will increase and the drainage area will decrease as more tailings are deposited into the impoundment. Hydrographs and several computer models, such as HEC (Army Corps of Engineers Hydrologic Engineering Center) and SWMM (Storm Water Management Model), are available for calculating runoff volumes. (Huber 1993)

Large volumes of rainfall and snowmelt in a short period of time can result in erosion of access roads, dike damage, contamination of surface water, and catastrophic failure of a tailings dam. A dam design includes plans to contain or mitigate runon volumes and rates associated with a flood. The type of flood used in a design depends on impoundment size, dam height, and the consequences associated with death, economics, and environmental damage. Designs provide protection from a return-period flood (e.g. 100-year) or an ultimate flood (defined as the maximum volume of runoff from a single event). A flood design involves the determination of rates and volumes associated with inflows and outflows in a dam as a function of time. Because tailings impoundments are intended for permanent disposal (i.e., over 10 or 100 years, the most common return intervals used), it may be appropriate to consider much longer return intervals (and/or extended care).

Infiltration

Infiltration rates are generally low because of the small particle size and low permeabilities in the tailings. Infiltration rates are a function of a soil's moisture content, capillary pressure, unsaturated hydraulic conductivity, and the distance below the surface. There is no runoff or ponding when the infiltration rate is less than the saturated hydraulic conductivity. Runoff or ponding occurs when the infiltration rate is larger than the infiltration capacity and the saturated hydraulic conductivity.

Evaporation

Evaporation is a function of wind velocity, atmospheric pressure, temperature, and areal extent of surface water. In general, it is proportional to the surface area of the free-water pond. Impoundments in arid areas are designed to conserve and recycle water for mining processes during the mine's active life. Evaporation data for certain areas are available from NOAA. Pan evaporation tests can be used to determine evaporation rates if the site is not located in a basin monitored by NOAA. In essence, the pan evaporation test monitors daily water loss in a Class A pan (four feet in diameter and ten inches deep) which is mounted one foot above the ground. A pan coefficient (0.64 to 0.81) is used to adjust pan evaporation rates because they will be higher than normal lake evaporation rates. When the evaporation rates for a basin are known, the designer can determine if surface area dimensions will provide the required evaporation rates. Because net evaporation, like precipitation, is not constant from year to year, it may be beneficial to reduce the calculated evaporation rate by a safety factor to account for annual variability.

5.1.2 Surface Water Controls

Each site requires a slightly different network of surface water controls because of differences in topography, climate, hydrology, geohydrology, etc. Most controls are a combination of storm event, flood event, seepage control, recycling, and dewatering processes. Methods for control can be first used in the design phase by siting the impoundment as far up-valley as possible. One step in minimizing the volume of water in and seeping from the impoundment can be accomplished by minimizing runon from outside sources through diversion of existing streams and run-on. This will in turn reduce size requirements for the impoundment.

The storage capacity of a dam affects the size of runoff control structures, applicability of some control structures, embankment size, and safety factors of a design. In turn, it is affected by the velocity, volume, and frequency of runoff in the basin. In general, the inflow plus the storage available in the dam has to equal the outflow from the dam. The maximum storage occurs when the inflow equals the outflow.

In some cases, storm flows are managed by increasing the freeboard in the impoundment during design; however, this results in additional water in the impoundment available for seepage. Using freeboard may be economical in semi-arid areas where flooding occurs infrequently and the mine requires a large amount of water for processing streams.

The principal methods for controlling runon are catch basins and check dams, and diversion ditches (channels and pipes). Catch basins stop surface water from entering the tailings impoundment area but generally require some method of by-passing the tailings impoundment such as decant systems or diversion ditches. Catch basins may be expensive because of labor and fill material but can be cost-effective for small runoff volumes. Treatment of the water may not be necessary because the water never enters the tailings impoundment itself. Water rights claims and environmental effects are important aspects of this alternative because the frequency and volume of water releases from the catch basin will affect downstream areas.

Decant systems are generally used in conjunction with other forms of surface water control. Major costs associated with the decant systems are pumping, maintenance, and treatment costs. It may be difficult, in areas with large surface water runoff volumes, to provide enough wells for removal of the runoff in a timely manner.

Diversion channels (open and closed) can be used for most dam designs, especially valley-bottom dam designs. Closed channels (pipes) are usually used under cross-valley dams because the dams generally do not permit a side channel for diversion. Water treatment is not an issue with diversion channels if they begin diverting the runoff above the dam. However, the long-term viability of diversion channels must be considered in design.

Spillways generally are designed as temporary structures because they will change (i.e., be moved or increase in length) as raised embankments increase in height. They are constructed of an impervious material able to withstand rapid flow velocities. The spillway also is designed to contain and control hydraulic jumps that occur at the bottom of the spillway. In addition, a spillway design has to consider and plan for water treatment if the surface water runoff passes through the tailings dam.

5.2 Tailings Seepage

As discussed previously, flow nets and other analytical methods can be used to calculate seepage volumes. A less conservative method for estimating seepage is use of a mass balance approach, assessing each of the potential inflows and outflows to determine overall water movement (Ferguson, et al. (1985).

5.2.1 Seepage Flow (Direction and Quantity)

Seepage is the movement of water (contaminated and uncontaminated) through and around the dam and impoundment. Primary factors affecting the volume of seepage present in a system are depth to the ground water table and infiltration capacities of the unsaturated zone and tailings. The quantities and water quality of the seepage affect the types of controls that are incorporated in the dam design. (Vick 1990)

Historically, controlled seepage through embankments has been encouraged to lower the phreatic surface and increase stability. Evaluation of the volume and direction of seepage is conducted using hydraulic principles similar to those used in embankment design. The same variables that are used during the design phase to predict the phreatic surface can be used to estimate the volume of seepage flow. Similarly, variables, such as permeability of the embankment and foundation, that might affect the phreatic surface also affect seepage rates and volumes. However, more exact and extensive data may be required than for calculation of pure pressures for analysis. Flow characteristics of tailings impoundments, their foundations, and underlying soil can be viewed as an inter-related system, with both saturated and unsaturated components.

Seepage evaluation can require information on: (1) components from geologic, hydrologic, and hydrogeologic studies, and (2) physical and chemical characterizations of surface water inflows, seepage, and tailings. Geologic factors affecting seepage are fractured rock, clay lenses, and uplifted geologic formations with large differences in permeability. Hydrologic data is affected by rainfall intensity, soil type, and surface conditions. This data can be used to calculate infiltration rates. Hydrogeologic studies can determine: (1) the critical path and degree of anisotropy of the ground water, (2) the boundary conditions for ground water flow evaluations, (3) the moisture content, permeability, and porosity of the tailings and underlying soil, (4) the thickness of the unsaturated zone and capillary fringe, and (5) the storage capacity, hydraulic conductivity, and transmissivity of the tailings and underlying aquifer. Flow nets and more complex models of seepage flow can be prepared. A mass balanced approach can also be used and is presented by Ferguson et al. (1985). For additional information on the determination of seepage volumes and direction, see Vick (1990), CANMET (1977), and Ritcey (1989).

5.2.2 Seepage Quality

The chemical composition of tailings seepage is important in determining potential environmental impacts. Factors include waste characteristics such as mineralogy of the host rock and milling methods used to produce the tailings, and the interaction of the tailings seepage with the liner (if any) and the subsurface. (Vick 1990)

Contaminant mobility can be increased by physical mining processes such as milling (a small grind results in increased surface area for leaching). Most mining companies manipulate pH and use chelating agents to extract minerals from the ore. These same processes can be applied to the fate and transport of contaminants in tailings. While many heavy metals are hydrophobic with strong adsorption tendencies for soil, the chemical reagents used in mining processes may be present in the tailings material. They are able to desorb the metals, making them mobile in leachate or surface waters.

Contaminated water may be formed from downward migration of impoundment constituents or ground water movement through tailings. Most contaminant transport in ground water systems is from the advection (fluid movement and mixing) of contaminants. Factors affecting the rate of advection include ground water/leachate velocity, chelation, pH, and partition coefficient values. The geochemistry of the aquifer, physicochemical properties of the tailings and seepage will determine the buffering capacity of the soil, types of chemical reactions (precipitation or neutralization) and the rate of adsorption and ion exchange.

A related problem is the production of acid by oxidation of thiosalts, which is a problem for some metal mines in eastern Canada. The bacterial culprit is thiobacillus thiooxidans. Thiosalts may be removed from the mill effluent by biological treatments (Guo and Jank 1980, quoted by Vick 1990).

According to Vick (1990), neutralization, oxidation/reduction, precipitation adsorption, ion exchange, and biological reactions play a major role in the chemical composition of tailings seepage. These are many of the same reactions used in milling operations to free the desired mineral. Seepage quality can be modeled using complex geochemical methods. Vick (1990) and Ritcey (1989), among others, describe the methods in some detail.

5.2.3 Seepage Control

There are two basic options for controlling contaminated water in impoundments: keeping it in the impoundment or capturing it after it exits the impoundment. Seepage controls are typically evaluated in the early phases of impoundment design. The objectives are to maintain embankment stability, decrease water losses, and maintain water-quality at the site. Options for seepage control include installation of liners beneath the entire impoundment (to contain water and to exclude ground water), constructing drains for seepage collection, constructing seepage collection and pumpback (or treatment) systems, sometimes in conjunction with low permeability barriers, construction of low permeability embankments and embankment barriers (i.e., cores and liners), dewatering of tailings prior to deposition, and decreasing hydraulic head by locating the free-water pond away from the embankment. Some of these techniques are described in more detail below.

Liners

Liners have not been incorporated into tailings impoundment designs until the last decade or two. Even now, due to their high cost, mining companies tend to avoid the use of liners under an impoundment. Although liners may be used to seal the upstream face of a tailings dam, most tailings impoundments in use today do not contain a lining system. The two major types of liners used to control flow through tailings dams are synthetic materials, which are very expensive, and constructed liners made of local clays or other readily available materials. Slimes are also sometimes used as low permeability barriers.

Areal coverage needed for the impoundments is a major cost consideration, especially for cross-valley dams. Thicknesses vary depending on the liner type but most thicknesses can be decreased if they are overlain with a drainage system to collect fluids, which reduces the hydraulic head (and stress) on the liner. An underdrain or vents may be necessary to remove sub-grade vapors that might otherwise lift the liner and to prevent ground water infiltration into the tailings. Liners have to be resistant to constituents in the tailings and seepage (such as acids or caustic substances), weathering if exposed to ultraviolet radiation, deformation from loading stresses, and seismicity.

Clays and synthetic liners can be combined to form double and triple liners. To prevent large settlements, clay and synthetic liners are not placed over loose or easily compressed material. Designs usually incorporate covers to mitigate the effects of sunlight, wave, and wind exposure on clay and synthetic liners, and drying on clay liners. The effects of frost action and drying are incorporated as needed into a liner design, especially for dams with sloped bottoms. Leakage can occur through synthetic liners because of shrinkage, faulty seam construction, stress loading, exposure to ultraviolet radiation, or improper planning and construction of the sub-grade. Short-term maintenance plans are generally implemented, because many problems often occur within the first six months of operation.

Clay Liners

Clay can be an inexpensive option for liners, especially in areas with a natural abundance of this material. Clay liners vary in thickness at least two feet, provide permeability of 10^{-6} cm/sec or less, and undergo physical-property tests such as permeability, Atterberg limits, moisture content, compaction, shear, and compression. The Standard Proctor compaction test, the most commonly used test, compacts the soil by a drop hammer in a standard mold. (The soil is compacted in three even lifts, using 25 blows per lift from a 10-lb hammer dropping freely through 18 inches.) From the compaction curve, the water content vs. dry unit weight, and the optimum moisture content can be determined. The optimum moisture content produces the maximum dry unit weight for the material. The primary factors affecting compaction characteristics are soil type and compaction energy.

The density of a clay liner depends on its mineralogy and the method and degree of compaction. Clay can be compacted to a prescribed moisture content and density to provide a permeability of 10^{-6} to 10^{-7} cm/sec or lower. Grain-size distribution curves may be used to determine the amount of fine-grained material in the clay. In general, a high-plasticity clay will be more desirable than a low-plasticity clay because of its lower permeability, but construction and the climate of the site may have an effect on the decision. Chemical tests are undertaken on the clay material to determine if it is resistant to the seepage produced by the tailings dam. Clay liners may be supplemented with other liners (e.g., synthetic) to further reduce potential seepage.

Clay liners can fail when their permeability increases considerably above the design value. According to Van Zyl, et al. (1988), the three major causes of failure are differential settlement of the foundation, causing localized cracking of the clay liner; drying of the clay liner (desiccation), leading to the development of microcracks (that can occur in areas lined with clay too long in advance of the time when wet tailings will cover the liner or if the tailings dry after deposition); and alteration of the liner permeability, due to geochemical reactions between the liner and leach solution.

Synthetic Liners

Synthetic liners are a relatively new development in the control of seepage in tailings impoundments. Of the rigid liners, concrete (rarely used) and gunite may be susceptible to acid and/or sulfate attack, and asphaltic concrete may have questionable weathering and sun-aging characteristics (Kays 1977). Sprayed membranes have demonstrated installation problems which may need to be resolved before being considered as a possible option. Synthetic rubber membranes (butyl rubber, EPDM) may be too costly for tailings impoundments (Vick 1990). Vick provides a discussion on some of the specific characteristics of these materials, their design, and effectiveness. These thermoplastic membranes are the most common liners considered for tailings impoundments.

Estimates of seepage through a liner can be made using Darcy's Law. Non-rigid liners are often grouped into a category called geomembranes. Geomembranes are often used in conjunction with clay liners to form a double or triple liner combination. Seepage losses through geomembranes are estimated on the basis of flow through a hole in the geomembrane. Most synthetic liners are resistant to acids, bases, and salts present in tailing dam seepage. Permeabilities for the liners are generally 10^{-9} to 10^{-14} cm/sec with average thicknesses of 40 to 60 mils (CMA 1991). As noted elsewhere, both the cost and technical feasibility are major factors in selecting synthetic liners, given the large size and uneven terrain usually encountered.

Slimes

Tailings slimes are easy and inexpensive to install as low permeability layers to slow but not stop seepage. To be cost-effective, the slimes must constitute a majority of the whole mill tailings and the coarse and fine sands must be cycloned out of the slimes. In addition, there should be a system in place to guarantee even distribution of the slimes in the tailings pond (using rear, forward, and side spigots). Slimes are often used to line the upstream face of tailings dams (or lifts). Although slimes may offer a low-cost alternative to other materials, they have several disadvantages that are discussed in Vick (1990) and Ritcey (1989). In addition, it is difficult to determine long-term permeabilities of the slimes.

Embankment Barriers

Embankment barriers are installed below the impoundment and include cutoff trenches, slurry walls, and grout curtains. An impervious layer of fill is generally required between them and the tailings. Barriers are installed underneath the upstream portion of a downstream embankment and the central portion of centerline embankments; they are not compatible with upstream embankments. A good water-quality monitoring program is needed when using embankment barriers to ensure that they are completely effective in intercepting flows and also that seepage is not moving downward and contaminating the ground water.

Cutoff trenches, usually 5 to 20 feet in depth, are the most widely used type of embankment barrier for tailings dams, especially in areas with large volumes of natural clays. Dewatering may be necessary during the installation of cutoff trenches when they are installed below the ground water table.

Slurry walls are narrow trenches that are best suited to sites with a level topography and containing saturated or fine-grained soils. They are not compatible with fractured bedrock systems. The slurry walls are installed by excavating a trench to a zone of low permeability material and filling the trench with a soil/bentonite slurry which is then allowed to set to a consistency of clay. Depths average 40 feet and permeabilities obtained can be as low as 10^{-7} cm/sec.

Grout curtains use cement, silicate materials, or acrylic resins as a barrier to seepage movement. They are limited to sites with coarse-grained material (medium sands to gravel or fractured rock with continuous open joints) and can extend to depths of more than 100 feet. Permeabilities obtained can be as low as 10^{-8} cm/sec. However, leaks can occur through curtain joints or by subsequent corrosion of the curtain. (Vick 1990)

Rather than simply intercepting and containing seepage flows, barriers may have gravel (or other pervious material, appropriately filtered) drains immediately upgradient to allow seepage to be removed or directed to embankment underdrains. Barriers and seepage collection systems also may be used downgradient of embankments to prevent further environmental releases.

Pumpback Systems

Pumpback systems consist of seepage ponds and/or seepage collection wells installed downgradient of the impoundment that are outfitted with pumps that send seepage back to the impoundment or for use as process water. Current practices include the use of toe ponds or seepage ponds to collect seepage. In some cases, underdrains or toe drains are designed to flow into the seepage pond. In other cases, however, these systems are installed after construction of the impoundment as a remedial action to collect unanticipated seepage. These units may be used in conjunction with slurry walls, cutoff trenches or grout curtains to minimize downgradient seepage. Depending on effluent quality, the operation of the pumpback system may continue indefinitely.

5.3 Tailings Water Treatment

Tailings ponds can be effective in clarifying water prior to discharge. Many factors influence the effectiveness of the pond to provide sufficient retention time to permit the very fine fractions to settle before reaching the point of effluent discharge or time for unstable contaminants to degrade. Factors affecting settling time are the size of grind, the tendency to slime (particularly with clay type minerals), pH of the water, wave action, depth of the water, and distance between the tailings discharge and the effluent discharge. Although settling velocities of various types and grain sizes of solids can be determined both theoretically and experimentally, many factors influence effectiveness of the decant pool as a treatment device.

The grind required to liberate the valuable mineral is usually under the #200 sieve. Particles in the range of 50 µm with a settling rate of 0.05 in/sec (0.12 cm/sec) can be affected by grind action but will settle in a reasonable time. Particles of 2 µm or less can cause a turbidity problem. Such particles have settling rates of less than 0.01 in/sec (0.025 cm/sec) in still water and, under conditions prevalent in most tailings ponds, require several days to settle due to the turbulence caused by wave action.

Observations of existing ponds has led to general rules for clarification. The pool should provide 10 to 25 acres of pond area for each 1,000 tons of tailings solids transported each day and should provide 5 days retention time. An average of 15 acres per 1,000 tons is usually considered adequate (CANMET 1977).

6. CASE STUDY: STILLWATER MINING COMPANY TAILINGS IMPOUNDMENT

In the early 1980s, Stillwater Mining Company was planning for the development of a platinum and palladium mine approximately 77 miles southwest of Billings, Montana. The State of Montana Regulations require a mine to submit an application for hard rock mining and to obtain a permit for hard rock mining before construction of the mine and mine facilities may begin (exploration activities may continue during the permitting process).

The design for engineering report for the Stillwater tailings impoundment was submitted to the Montana Department of State Lands in February 1987. Its purpose was to present comprehensive information on all the activities that had been conducted at the site in relation to the design of the future tailings impoundment and to present the design to accommodate the engineering criteria developed as a result of the site evaluation, the tailings characteristics, the environmental regulations and future operations. The report included a scope of work that indicated the various tasks that had been completed in the conduct of the study. These tasks were listed as follows:

- Prepare design basis memoranda of the project design criteria,
- Supervise soil drilling, test pit excavations, and field density testing.
- Prepare and administer laboratory test programs for soils and tailings.
- Perform static and pseudo-static stability analyses and estimate the seismically-induced deformations of the dam due to the Maximum Credible Earthquake event.
- Perform hydrological studies to determine design flood runoff to the impoundment and water profile curves on adjacent natural waterways resulting from designated flood events.
- Perform reclamation studies to design a tailings drainage system.
- Select appropriate impoundment liner materials.
- Estimate construction material quantities and prepare construction sequencing curves showing required embankment crest elevation and tailings elevation versus time.

- Prepare inspection, maintenance, and contingency plans.
- Prepare design drawings of the initial, final, and reclaimed impoundment stages.
- Prepare an engineering report.
- Prepare plans and technical specifications sufficient for construction permitting.

6.1 Site Evaluation, Field Exploration and Laboratory Tests

6.1.1 Site Evaluation

The consultants responsible for all aspects of the tailings impoundment design performed their first reconnaissance of the site in August 1983. The purpose of this visit was to observe the foundation of the proposed tailings disposal area, determine if evidence of potential landslides and faulting existed at the site or in the vicinity of the site and to search for materials that could be used in the construction of the impoundment. The results of this reconnaissance, and previously collected information from a past drilling effort, indicated that the foundation beneath the proposed site was composed of pervious materials, gravels and boulders in a silty sand matrix. Prominent unweathered granite outcrops were noted as abutments to the tailings impoundment dam. Landslide materials were noted above the tailings impoundment area but were determined to be stable based on the natural slope and the lack of evidence of instability (ground cracking and leaning trees). Faulting and shearing were noted in the granite outcrops immediately west of the proposed impoundment, the geologist conducting the reconnaissance indicated that the fault was not active and will not have the potential for cracking of the tailings pond lining.

6.1.2 Field Exploration

A seismic refraction survey conducted in the impoundment area in 1983 determined the depth of bedrock to range from 31 to 226 feet below ground surface in a trough-shaped valley.

Test pits excavated up to 22 feet below ground surface in 1983 and 1985 explored ground conditions in the pond and dam foundation areas. In-place field density tests were conducted in 14 of the pits, nine in the location of the proposed dam foundation. The upper one to two feet of the test pits consisted of brown silty and sandy soils and below this soil horizon the material in the pit was largely composed of sand, gravel, cobbles and boulders with only 2 to 17 percent silty fines. Building rubble (left from a previous mining venture), abandoned pipelines and other non-native materials were uncovered during the excavation of the pits. The average dry density of the soil in the bottom of the pits was determined to be 135 pounds per cubic foot and the average dry density was determined to be 130 pounds per cubic foot. The results of the seismic refraction surveys indicated that soil densities increased below the bottom of the test pits.

Eight monitoring wells drilled in the impoundment area between 1979 and 1983 provided baseline ground water information and foundation conditions. The ground water surface ranged from 40 to 100 feet below the ground surface, but bedrock in the western portion of the proposed impoundment was found to form a ground water boundary and wells located west of this area were dry. Five soil borings ranging from 54 to 74 feet deep were drilled into the foundation area. Standard Penetration Test (ASTM D-1586) was used during the drilling, but the results were used only to qualitatively evaluate the density of the sands and gravels. Representative soil samples removed during the drilling were sent for laboratory evaluation.

6.1.3 Laboratory Tests

Laboratory tests of the borrow materials to be used in the proposed embankment and the foundation soils included grain size analyses (both sieve and hydrometer), Atterberg limits, natural moisture contents and specific gravity. Atterberg limits tests indicated that the fines display little to no plasticity. Natural moisture content was determined to range between 1 and 7 percent. Triaxial compression tests were also performed on borrow materials to be used in embankment design. The resulting strength parameters were used in preliminary stability analyses. Consolidated-undrained triaxial compression tests with pore pressure measurements were performed on recompacted samples of embankment borrow materials and foundation materials.

In the triaxial compression tests, foundation soil samples recompacted to the average foundation dry density determined in the field (130 pcf) were determined to have an effective angle of internal friction of 35 degrees and an effective cohesion of zero.

Laboratory compaction test results showed that the maximum dry density of the impoundment sands and gravels (embankment materials) range from 148 pcf to 159 pcf with optimum moisture contents ranging from 5 to 8 percent. The high density of the materials is attributed to their high specific gravity (3.0 to 3.2).

In the triaxial compression tests, the impoundment soil samples were compacted to 95 percent of the maximum dry density determined by ASTM D-698 (140 pcf). The effective angle of internal friction was determined to be between 39 and 41 degrees with an effective cohesion of zero.

Laboratory tests were also undertaken for tailings produced from a pilot grind on the mine site ore. Only fines were tested (cyclone overflow) since coarse tailings were to be deposited underground. Gradation, Atterberg limits and specific gravity were determined for the sample as well as sedimentation tests to determine the settled tailings density. Consolidation tests were conducted to estimate the variation of tailings density with depth and time-rate settlement characteristics.

Mine waste rock was also proposed for use in the construction of the dam embankments, however, no results of field or laboratory testing were presented in the engineering report. Results of visual observations noted that the rock was moderately well graded from fine rock dust to 24 inches, with the greatest proportion of materials in the 3 to 6 inch range. The rock was described as moderately hard with angular sharp edges. Debris (pipes, wood, plastic tarps and wire mesh) was noted mixed in with the waste rock.

6.2 Office Evaluations

The hydrology evaluations and stability analyses required for tailings dam design can be accomplished using results of the field and laboratory tests as well as maps and published data and information.

6.2.1 Hydrology Evaluation

The Stillwater River flows approximately south to north just east of the tailings impoundment site. A small tributary of the Stillwater River, Mountain View Creek, lies just south of the tailings impoundment. The toe dike was designed to be located 200 to 300 feet west of the Stillwater River and 50 feet north of Mountain View Creek.

The watersheds for both the Stillwater and Mountain View Creeks were estimated as well as the tailings impoundment and tailings impoundment catchment areas. These were presented in the engineering report as follows:

Watershed	Drainage Area	Average Basin Elevation
Tailings Impoundment Catchment	68 acres	5500 feet
Final Tailings Impoundment	35 acres	
Mountain View Creek	1.48 square miles	7300 feet
Stillwater River above Mountain View Creek Confluence	191 square miles	9000 feet

Flow records from the gaging station nearest the mine site with a long period of record (located 25 miles downstream of the site) shows that the maximum recorded flow was 12,000 cfs. The drainage area at this location is 975 square miles.

The flood storage volumes for the impoundment were determined to size the impoundment to prevent overtopping. The design flood for the impoundment is based on size and downstream hazard potential classifications as found in the U.S. Army Corps of Engineers "Recommended Guidelines for Safety Inspection of Dams". Guidelines recommend that the design flood for this impoundment should range from one-half the probable maximum flood (PMF) to the full PMF. The one-half PMF was chosen as the design flood for the impoundment at intermediate heights and the full PMF was chosen for the impoundment at stages which exceed a height of 100 feet.

The PMF and one-half PMF estimates were determined for the Tailings Impoundment Catchment Area, the Mountain View Creek Watershed and the Stillwater River Watershed above the confluence with Mountain View Creek. The Army Corp of Engineers' Hydrologic Engineering Center (HEC) computer programs, used to determine flood hydrographs (HEC-1) and water surface profiles (HEC-2), were employed in the estimation effort.

Other basic data for use in the PMF study were pulled from a number of sources. The probable maximum precipitation (PMP) for Six-hour local and 72-hour general storms were developed from the "Hydrometeorological Report No. 55, Probable Maximum Precipitation Estimates - United States, Between the Continental Divide and the 103rd Meridian". The PMP for 72-hour storms assumed unlimited snowpack available for snowmelt since the maximized storms occur primarily from the end of May through June (spring melt season). Snowmelt estimates were based on the Army Corp of Engineers' "Runoff from Snowmelt" since actual data on local snowpack and snowmelt were not available. Temperatures and windspeeds during the PMP were calculated following the procedures in the "hydrometeorologic Report No. 43, Probable Maximum Precipitation, Northwest States". Unit hydrographs, infiltration and retention losses were developed from the Soil Conservation Service procedures.

The results of the HEC-1 computer program determined the following results of the design floods, as shown in Table 2.

Table 2. Stillwater Mining Company Calculated Design Floods

Design Storm	Tailings Impoundment	Mountain View Creek	Stillwater River above Confluence with Mountain View Creek	Stillwater River below Confluence with Mountain View Creek
PMF (72-hr. PMP plus snowmelt) volume	312 acre-feet			
1/2 PMF (72-hr. PMP plus snowmelt) volume	156 acre-feet			
PMF (6-hr. local storm PMP) peak discharge		11,230 cfs		
1/2 PMF (6-hr. local storm PMP) peak discharge		5,615 cfs		
PMF (72-hr. PMP plus snowmelt) volume		8,241 cfs	329,980 cfs	330,828 cfs
1/2 PMF (72-hr. PMP plus snowmelt) volume		4,121 cfs	164,990 cfs	165,414 cfs

The HEC-2 water surface profiles computer program was used to determine the estimated maximum water surface elevations and flow velocities for the PMF and 1/2 PMF peak discharges at the stretch of the Stillwater River opposite the tailings impoundment. The river sections (cross sections and longitudinal sections) were assumed to be stable, with no scour or bank sloughing. This is of a conservative assumption since scour is likely to occur during a flood of PMF magnitude and the scour would widen and deepen the channel. The computed surface water elevations resulting from the PMF on the Stillwater River were shown to locally exceed the design toe dike by 15 feet, however, this left 5 feet to the top of the toe dike. The 1/2

PMF exceeded the bottom elevation of the toe dike by about 4 feet and the distance left to the top of the toe dike was 16 feet. The toe dike is beyond the limits of the computed 100-year and 500-year flood plains.

Velocity calculations indicated that erosion would occur under PMF and 1/2 PMF conditions on both the Stillwater River and the Mountain View Creek. The 1/2 PMF storm was not considered to be of sufficient extent to cause total failure of the dam. The PMF storm was considered to create sufficient erosion to cause total failure of the dam.

6.3 Tailings Impoundment Design

At the Stillwater Mine, whole tailings were to be separated by cycloning into the coarse and fine fractions; coarse fractions were to be deposited underground and fine fractions were to be placed in the lined tailings impoundment.

The engineering plans for the tailings impoundment indicate that whole tailings on occasion may be deposited in the tailings impoundment. A total tailings production rate of 500 dry tons per day during the first 4 years (approximately half that to be disposed in the impoundment as fine tailings) were estimated for tailings design. From year 5 forward a total tailings production rate of 1000 dry tons/day (approximately half that to be disposed in the impoundment as fine tailings) were estimated for tailings design. Tailings production was estimated to occur 330 days per year, 24 hours a day. The tailings were assumed to have a solids content of 30 percent and the fine fraction was assumed to have a solids content of 18 percent.

The tailings impoundment design, a side hill modification, calls for the embankment to be raised in four stages throughout the life of the mine. This layout and the final dam crest elevation were based on the preliminary studies and a mine life of 20 years. The maximum height of the dam will be 130 feet and the crest width was designed to be 20 feet to accommodate vehicle traffic and a tailings slurry pipeline. The upstream slopes of the dam were designed at 1.6:1 and the downstream slopes at 2:1 as determined through static and dynamic stability analyses.

Impoundment excavation will occurs in stages one and two to provide construction materials for the embankment and to increase the storage capacity of the impoundment. Each new stage of the embankment will be added in the downstream direction.

The embankment stage and estimated stage life statistics are listed below as based on a 1987 startup date.

Stage Number	Dam Crest Elevation	Approximate Year Dam Stage Construction Completed	Approximate Year Stage Filled
1	5045	1986	1992
2	5077	1991	2002
3	5096	2001	2007

4	5102	2006	2009

The impoundment was designed to store the design flood volume. The design freeboard (3 feet while containing the design flood volume) was determined from the flood storage volume and operational considerations.

The impoundment was to be monitored for settlement using survey monuments located along the dam crest. Piezometers were to be installed in the dam foundation to monitor for seepage.

The design calls for the installation of a synthetic liner to minimize the migration of effluent from the impoundment to ground water. The installation of the liner was planned in stages to coincide with the embankment raises. This plan not only reduces cost but also prevents potential damage to portions of the liner that would have been exposed for many years. The liner was selected based on economy, chemical resistance, resistance to weather, constructability and strength and durability. Hypalon and HDPE liners were being tested at the time of the engineering report. Based on initial tests (simulations of the tailings pond environment), it appeared as though the HDPE liner experienced no changes to its material properties while the Hypalon liner was experiencing some changes in material properties. Installation procedures for the liner required the removal of all objects (rocks, clods, debris, sharp objects, etc) that could potentially damage the liner. As-built figures have not been obtained.

In order to complete evaluation of the effectiveness of lining the tailings impoundment, additional information is needed. However, this tailings impoundment example shows that the mining industry is investigating options for lining tailings impoundments and that in some cases, liners may be a feasible alternative. This case study exemplifies the amount of study necessary to assess the feasibility of using a synthetic liner. Additional studies (which were not obtained prior to preparation of this report) may provide an analysis of the water balance and how it has been affected by the synthetic liner. Final cost analysis (also not obtained) will help to provide a measure of the feasibility of lining impoundments with synthetic liners. This impoundment design has been approved by the State of Montana and the impoundment is currently operating as planned, providing an example showing that lining of impoundments can be a feasible option to minimize seepage and environmental impact.

7. REFERENCES

Bedient, P.B. and W.C. Huber. 1989. *Hydrology and Floodplain Analysis*. Addison-Wesley: Menlo Park, 650 pages.

Bishop, A.W. 1955. "The Use of the Slip Circle in the Stability Analysis of Slopes." *Geotechnique*, Vol. 5, No. 1, pp. 7-17.

Bishop, A.W. 1971. "The Influence of Progressive Failure on the Choice of the Method of Stability Analysis." *Geotechnique*, Vol. 21, No. 2, pp. 168-172.

Brawner, C.O. and D.B. Campbell. 1973. "The Tailings Structure and its Characteristics - A Soil's Engineer's Viewpoint." In: *Tailings Disposal Today*, Proceedings of the First International Tailings Symposium, Tucson, Arizona, October 31, November 1, 2 and 3, 1977. C.L. Aplin and G.O. Arsall Jr. (Editors).

California Mining Association. 1991. *Mine Waste Management*. Sacramento, CA.

Canadian Centre for Mineral and Energy Technology (CANMET). 1977. *Pit Slope Manual*. Chapter 9: Waste Embankments.

Canadian Centre for Mineral and Energy Technology (CANMET), Mine Environment Neutral Drainage (MEND) Program. 1993 (March 9). *1992 Annual Report*. CANMET, Toronto.

Canadian Geotechnical Society. 1989. "Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage." Proceedings of a conference held May 26, 1989, Vancouver, British Columbia.

Charles River Associates. 1985. "Estimated Cost to the U.S. Mining Industry for Management of Hazardous Solid Waste." CRA Report to the U.S. Environmental Protection Agency #730.

U.S. Army Corps of Engineers. 1974. "National Dam Safety Program, Proposed Guidelines for Safety Inspection of Dams." Federal Register Vol. 39, No. 168 (Aug. 28), p. 31331-31346.

Das, B.M. 1990. *Principles of Geotechnical Engineering*, Second Edition. PWS-Kent Publishing Corp., Boston, Massachusetts.

Dougherty, E.R. 1990. *Probability and Statistics for the Engineering, Computing, and Physical Sciences*. Prentice Hall: New Jersey, 800 pages.

Doyle, F.M. (ed.). 1990. "Mining and Mineral Processing Wastes: Proceedings of the Western Regional Symposium on Mining and Mineral Processing Wastes, Berkeley, CA, May 30 - June 1, 1990." Society for Mining, Metallurgy, and Exploration, Inc. Littleton, Colorado.

Environment Canada; Mining, Mineral and Metallurgical Processes Division. 1987 (December). *Mine and Mill Wastewater Treatment*. Report EPS 2/MM/3. Minister of Supply and Services Canada Catalog No. En 49-7/2-3E, ISBN 0-662-15788-5.

Environment Canada; Mining, Mineral and Metallurgical Processes Division. 1992 (December). *Environment Protection Series: Status Report on Water Pollution Control in the Canadian Mining Industry (1990 and 1991)*. Report EPS 1/MM/4. Minister of Supply and Services Canada Catalog No. En 49-7/2-3E, ISBN 0-662-20062-4.

Environmental Protection Agency, Huber, W.C. 1993. "Information on the EPA Storm Water Management Model (SWMM) Version 4.2." U.S. EPA, College Station Road, Athens, GA.

Fetter, C.W. 1980. *Applied Hydrogeology*. Columbus: Charles E. Merrill Publishing Co., 487 pages.

Ferguson, K.A., I.P.G. Hutchinsom, and R.L. Schiffman. "Water Balance Approaches to Prediction of Seepage from Mine Tailings Impoundments." In: *Seepage and Leakage from Dams and Impoundments*. 1985.

Gilbert, R.O., 1987, *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold: New York, 320 pages.

Giroud, J.P. and R.K. Frobel. 1983. "Geomembrane Products." Geotechnical Fabrics Report, Fall, pp. 38-42, {cited in Van Zyl, Hutchison, Kiel, 1988}.

Hawley, J.R. 1974. "The Use, Characteristics and Toxicity of Mine/Mill Reagents in the Province of Ontario." Ontario Ministry of the Environment, Toronto.

International Engineering Company. 1986. "Stillwater Tailings Impoundment Engineering Report." Prepared for: Stillwater Mining Corporation, February 1986.

Inyang, H. 1993. Personal Communication with Chris Long, SAIC, August 1993, concerning safety factors.

Kealy, C.D. and R. Busch. Undated. "Evaluation of Mine Tailings Disposal."

Klohn, E.J. 1981a. "Geotechnical Investigations for Siting Tailings Dams - Design and Construction of Tailings Dams." Proceedings of a Seminar November 6-7, 1980, Golden, Colorado.

Klohn, E.J. 1981b. "The Development of Correct Tailings Dam Design and Construction Methods-Design and Construction of Tailings Dams." Proceedings of a Seminar November 6-7, 1980, Golden, Colorado.

Lighthall, P.C. 1987. "Innovative Tailings Disposal in Canada." *International Journal of Surface Mining* 1.

Lighthall, P.C., B.D. Watts and S. Rice. 1989. "Deposition Methods for Construction of Hydraulic Fill Tailings Dams." In: *Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage*. The Vancouver Geotechnical Society, Vancouver, British Columbia, May 26, 1989.

McWhorter, D. and J. Nelson. 1979. "Unsaturated Flow Beneath Tailings Impoundments," *Journ. Geotech. Div., ASCE*, Vol. 105, #GT11, p. 1317-1334.

Mittal, H.K. and R. Hardy. 1977. "Geotechnical Aspects of a Tar Sand Tailings Dike." ASCE Conference on Geotechnical Practice for Disposal of Solid Waste Materials.

Mittal, H.K. and N.R. Morgenstern. 1977. "Design and Performance of Tailings Dams." ASCE Conference on Geotechnical Practice for Disposal of Solid Waste Materials.

Mittal, H.K. and N.R. Morgenstern. 1975. "Parameters for the Design of Tailings Dams." *Canadian Geotechnical Journal*, Vol. 13, p. 277-293.

Mittal, H.K. and N.R. Morgenstern. 1976. "Seepage Control in Tailings Dams." *Canadian Geotechnical Journal*, Vol. 12, pp. 235-261.

Parsons, M.L. 1981. "Groundwater Aspects of Tailings Impoundments, Design and Construction of Tailings Dams." Proceedings of a Seminar November 6-7, 1980, Golden, Colorado.

Randol International Ltd. 1985. Water Management and Treatment for Mining and Metallurgical Operations. Randol International Ltd., Golden, CO.

Ritcey, G.M. 1989. *Tailings Management: Problems and Solutions in the Mining Industry*. Elsevier Science Publishers, B.U. Amsterdam, The Netherlands.

Ritcey, G.M. and M. Silver. 1987. Deep Water Disposal of Pyritic Tailings - A Simulation. Unpublished data from CANMET.

Robinsky, E. 1979. "Tailings Disposal by the Thickened Discharge Method for Improved Economy and Environmental Control." Proceedings, 2nd Int. Tailing Symp., Argall, G. (ed.), Miller Freeman, San Francisco, pp. 75-95.

Ross-Brown, D.M. 1979. "Final Pit Limit Slopes - Analytical Design." Open Pit Mine Planning and Design. American Society of Mining Engineers.

Schabel, P. and H. Seed. 1973. "Accelerations in Rock for Earthquakes in the Western United States." *Bull. Seis. Soc. of Am.*, Vol. 63, No. 2, pp. 501-516.

U.S. Dept. of Agriculture, Soil Conservation Science. 1964. *SCS Engineering Handbook*, Section 4: Hydrology.

Smith, E.S. 1972. "Tailings Disposal - Failures and Lessons." *Tailing Disposal Today*, Proceedings of the First International Tailing Symposium, Tucson, Arizona.

Soderberg, Roy L. 1977. "Design Guide for Metal and Nonmetal Tailings Disposal." Information Circular No. 8755. United States Department of the Interior, Bureau of Mines. 1977.

Swaisgood, J.R., and G.C. Toland. 1972. "The Control of Water in Tailings Structures." *Tailings Disposal Today*, Proceedings of the First International Tailing Symposium, Tucson, Arizona.

United States Department of the Interior, Bureau of Mines. 1992. "RCRA Regulation Impact on Alaska Mineral Development—Tailings Management." Prepared by Steffen, Robertson, and Kirsten, Inc., Denver, Colorado, May 1992.

van Zyl, D.J.A., I.P.G. Hutchison, and J.E. Kiel. 1988. *Introduction to Evaluation, Design and Operation of Precious Metal Heap Leaching Projects*. Society of Mining Engineers, Inc., Littleton, Colorado.

Vick, S.G. 1990. *Planning, Design and Analysis of Tailings Dams*. BiTech Publishers Ltd.

Volpe, R. and W.E. Kelly. 1985. *Seepage and Leakage from Dams and Impoundments*. American Society of Civil Engineers.

Williams, M. 1979. "Tailing Dam Failure Case History." Proceedings, 2nd Int. Tailing Symp., Argall, G. (ed.), Miller Freeman, San Francisco, pp. 428-433.