TAILINGS MANAGEMENT USING QUANTITATIVE RISK ASSESSMENT

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Abstract

Releases of mine tailings effluents and solids from containment facilities around the world have heightened awareness that risk associated with tailings impoundments must be fully addressed during all phases of a mine life. The authors have developed a quantitative risk assessment process that allows mine owners and operators to quickly and successfully identify problem areas, and assess mitigative methodologies and priorities. The numerical method allows comparison between mines on a company wide basis and provides a platform for decision making as part of a risk management program. This paper focuses on how to conduct a quantitative risk assessment and provides a series of examples highlighting the principles involved and the advantages and disadvantages of using a quantitative risk assessment.

Introduction

Recent releases of tailing effluents and solids from containment facilities around the world, including Merrispruitt, 1994, Omai, 1995, and Marcopper, 1996, and Los Frailles, 1998, have heightened awareness for mine owners and mine operators that risks associated with tailing containment must be fully addressed during all phases of a facility life. The Mining Association of Canada (MAC 1998), has published a guide to the management of tailings disposal facilities. Four phases of an impoundment life have been identified including design, construction, operation and closure of tailing impoundments. The MAC guidelines propose a risk assessment be undertaken for each phase.

A risk assessment is a standardized or formalized method of review which, while helping to pinpoint exposure to hazards, will not eliminate them. Risk assessments should be seen as a management support tool allowing a corporation to develop risk based decision making, thus leading to optimum resource allocation and maximization of returns. Using risk assessments in this way is generally understood as “Risk Management”. A risk assessment does not replace sound engineering or sound knowledgeable tailings management practices.

Numerous risk assessments have been undertaken in the past 5 years on tailings impoundments and mine sites. Many of the projects have been undertaken using a Failure Modes and Effects Analysis (FMEA), a qualitative methodology where likelihood and consequences are evaluated in terms of descriptions. The FMEA allows a qualitative ranking of risks for each component as well as the system as a whole. The FMEA is a powerful screening tool which highlights areas of concern. The results can be compared qualitatively and can be compared locally but quantitative cost estimates are difficult to define.

The results of a qualitative approach, such as the FMEA, are expressed in terms of

Low Risk to High Risk usually in a form similar to that shown as Table 1 below.

Table 1
Generalized Risk Classifications

Consequences					
Very High	**Highest Risk VH/VH**	**VH/H**	**VH/L**	**VH/L**	**Low Risk VH/N**
High	**H/VH**	**High Risk H/H**	**H/M**	**H/L**	**H/N**
Moderate	**High Risk M/VH**	**M/H**	**Moderate Risk M/M**	**M/L**	**M/N**
Low	**L/VH**	**L/H**	**L/M**	**Low Risk L/L**	**L/N**
Very Low	**Low Risk VL/VH**	**VL/H**	**VL/M**	**VL/L**	**Negligible risk VL/N**
	Very High	**High**	**Moderate**	**Low**	**Negligible**
			Likelihood of Occurrence		

Where the risk categories are defined as outlined below.

▩	High Risk Classification: More work is required to define concepts and possibly assess the methodology and determine remedial action in the next 6 months.
▨	Moderately High Risk: More work is required to define concepts, quantify elements and determine remedial action in the next 6 to 12 months. unless the degree of confidence surrounding the Likelihood is low or medium in which case more work is required to define concepts in next 6 months.
░	Moderate Risk: Action plan needed within 6 to 12 months. Not a high priority. Undertake when funds available
	Low Risk: No significant additional work required.

The axes of the table provide qualitative assessments of the potential for a hazard to occur and an estimate of the level of consequences. The level of risk is defined in the matrix. Areas of High Risk or Moderately High Risk are identified with the intent of defining a remedial action to reduce the risk either by mitigating the hazard or reducing the consequences. The definitions of the terms High to Low are generally agreed upon prior to the start of the exercise. The FMEA analysis is a simple procedure which is useful for highlighting problem areas within any single given mine or project area but does not deliver easy to interpret quantitative results.

While the FMEA can lead to identifying areas of concern at one particular project, it does not allow quantitative comparisons between mines nor does it allow risk management on the basis of cost estimates. For larger mining corporations with several properties the ability to compare properties and allocate resources between sites becomes important and a Quantitative Risk Assessment (QRA) is recommended. The use of Quantitative Risk Assessment (QRA) is viewed as a means for rationalizing decision making in current times of financial constraints and limited budgetary resources.

Quantitative Risk Assessment

A QRA can constitute a preliminary step toward risk management of tailing containment facilities which in turn can minimize risk exposure for both existing and future mines. A QRA can be considered an integral part of the standardization of the design, construction, operation and closure of proposed and existing tailing containment facilities.

A quantitative risk assessment requires a numeric estimation of the probability of an event occurring coupled with a numeric assessment of the consequences of the event occurring or an assessment of the damage cost. The term risk is defined as the combination (a multiplication) of the likelihood of a specified hazard being realized and the consequences of the event (harm and/or damage). This definition is in compliance with recent standard definitions (Oboni and Oldendorff, 1997).

In addition to comparing the risk costs between sites, the advantage of the quantitative system becomes apparent when comparing the costs of mitigation using several potential techniques (Oboni et al, 1997). The capital costs of various solutions can be compared on an annual basis so that a rational means can be used to define how much of one's limited resources can be applied to give the most cost effective mitigation.

Because there is little in the way of published statistics for tailings impoundments, the authors have developed a process to provide a quantitative subjective estimate of the probability of occurrence of elemental failure modes. The use of quantitative subjective estimates of the probabilities leads to the notion of relative risks which could lead to a loss of tailing or supernatant impacting on the environment (Oboni et al, 1998). The risks associated with Acid Rock Drainage are discussed in a companion paper, (Mehling et al., 2000).

Assessment Process

A risk assessment process must contain the following steps:

- Identification and definition of the System Boundaries.
- Subdivision of the system into elements and links;
- Identification of hazards and elemental failure modes
- Evaluation of the probability of hazards and elemental failure modes occurring;
- Evaluation of potential targets and costs of failure;
- Determination of Risks.

A brief description of the methodology undertaken at each step is provided below.

Defining System Boundaries and Elements and Links

Bounding the system to include the potential for hazards outside the immediate footprint of the tailings facility is critical to the proper assessment of risk (Abbott et al, 1998a).

In order to define the physical limit of hazards that could impact the elements or links of a system, the maximum theoretical boundaries which encompass the area surrounding the system, need to be viewed. All too often the boundaries are limited to the slopes or crests of ridges visible from the area being assessed. The Matachewan Tailings dam failure in 1990 was a direct result of the failure of a beaver dam being constructed several kilometres upstream of an abandoned tailing facility.

The maximum theoretical boundary is the widest limits that would contain a hydrologic or catastrophic event that could directly or indirectly impact on the facility. For example the maximum theoretical boundary for a dam and reservoir could extend from ridge top to ridge top on either side of the containing valley. The Matachewan example cited above is a direct consequence of not extending the maximum boundaries far enough. The horizontal distance along the valley or perhaps in a tributary valley, within which an event could cause an impact on the facility in questions, requires significant consideration.

It is often not sufficient to view the boundaries from the elements being threatened. Under these circumstances, the extent of chutes, anomalous geomorphological entities and large scale instabilities which threaten the facilities are often not recognized. In order to best define the boundaries, a remote assessment using existing topographic and geologic maps, air photographs and satellite photographs and maps should be undertaken. Remote sensing and an understanding of the geologic environment surrounding the site is required to define hazard contours, areas of large scale phenomenon which could have an influence on the elements being addressed. An example of a large landslide which covers an entire valley and which impacts directly on a pipeline corridor and which is difficult to recognize without large scale photographs, is shown on Figure 1.

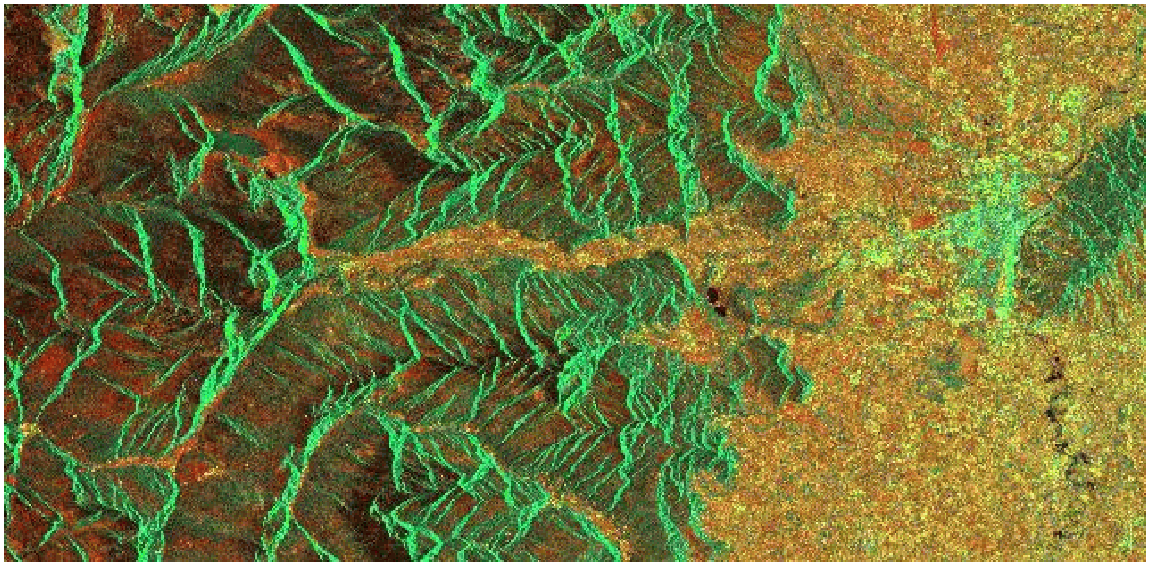

Figure 1. An example of remote sensing imagery used to define the limits of large-scale landsliding in a transportation corridor in Italy.

Subdivision of the System

In order to fully assess the risks of a tailing containment failure the "system" has to be subdivided into manageable sized components known as "elements" and "links". Elements are defined as facilities which store the tailings, supernatant or water and links are defined as facilities which transport the tailings or reclaim between the elements. Elements and links include but are not necessarily limited to:

- The mill area where tailings are collected then pumped to the containment facility, (Pumpbox);
- Tailing transport, deposition and reclaim pipelines and spill control systems;
- Tailing embankment including primary dam and any saddle dams;
- Tailing deposition beaches;
- Reclaim facilities;
- Ditches including diversion ditches and other stormwater controls;
- Groundwater monitoring and collection systems;

All ponds associated with tailings including polishing ponds.
An example of system definition with elements and links defined is shown on Figure 2.

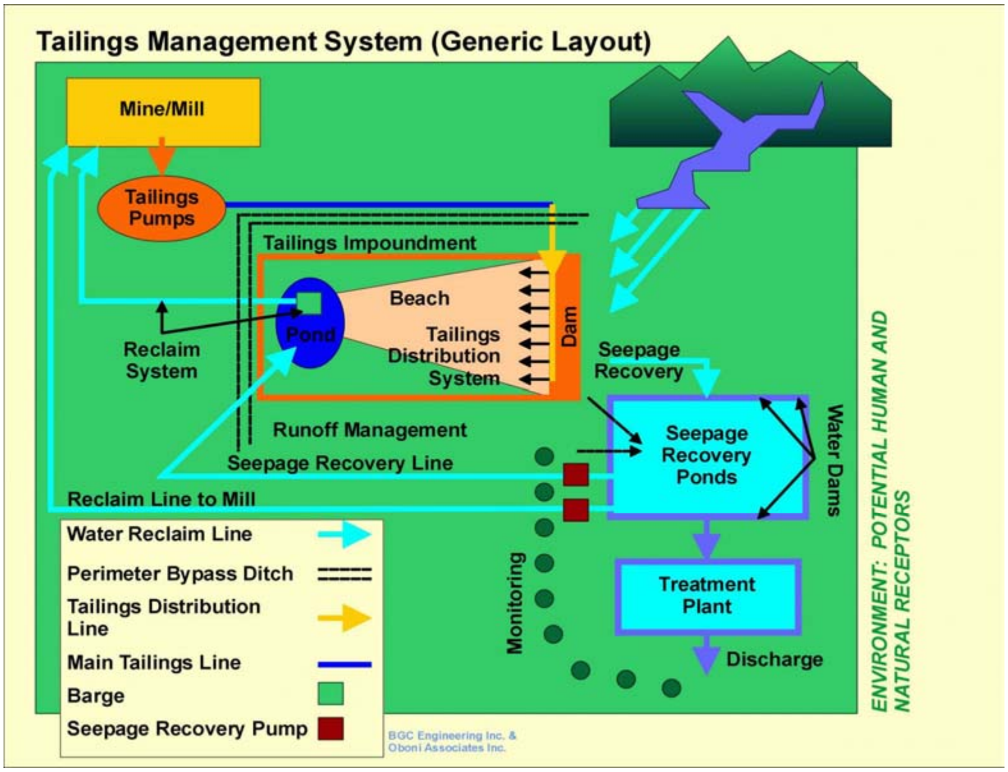

Figure 2. A generic model of a tailings containment system showing examples of elements and links which need to be defined.

Hazard Identification

An effective risk assessment initially requires identification of hazards or potential failure modes (Abbott et al, 1998b). Many of the hazards related to tailing containment facilities are unique to the mining industry. For example, mines, and in particular tailing containment systems, are constructed over long periods of time by a changing work force and usually under changing design criteria. Tailings systems are complex, process specific and include man-made components such as dams, pipelines and ponds interacting with natural components such as slopes, seismically active faults, precipitation and runoff. Tailing containment risk assessments are therefore unique to each mine.

A comprehensive risk assessment system must account for all types of hazards and the affected components existing at a specific site or location. To be effective the risk assessment approach must be systematic, yet accommodate the varying spatial and temporal considerations of each mine site.

In order to define hazards that can be identified repeatedly and managed easily, elemental Failure modes, those attributable directly to single external causes, are identified. Elemental failure modes cannot be subdivided further. Examples of elemental failure modes are:

- a pipe bursting as a result of mechanical failure;
- a pipe bursting as a result of a traffic impact; or
- a pipe bursting as a result of over pressurizing due to freezing or sanding.

In order to assess as many failure modes as possible and provide a template for comparison at each mine site, a series of potential failure modes have been identified based on previous historical data published by United States Committee on Large Dams, (Vick, 1994) and United Nations Environmental Program (UNEP, 1996). Examples of the elemental failure modes initially identified by the authors are summarized in Table 2. The list is continuously updated as new failure modes are identified.

Definition of Quantitative Probability of Occurrence

The quantitative system devised by the authors has been successfully applied at 8 mines, 6 industrial sites and two railroads (Abbott, 1998b; Oboni et al, 1998). The system uses subjective probabilities gained from expert interviews to provide initial probabilities of the occurrence of elemental failure modes, an assessment of the likelihood. This is later modified by expert judgement to reflect the state of the system. The first level of assessment provides an initial estimate of the probability of occurrence based on past performance or case history assessment. *I.e. has a particular mode of failure occurred in the past and if so how often?* The second level allows refinement of the initial assessment on the basis of expert opinion which takes into account the state of the existing conditions or the state of the system. *I.e. is there dense glacial till (good) or loose sand (bad) in the dam foundation?*

An example of the estimated probabilities of failure is provided as Table 3 below.

Table 2
Examples of Elemental Failure Modes for Impoundment Systems

Reservoir (overtopping)
Landslide into reservoir generates a wave which overtops the dam
Wave action overtops dam
Perimeter bypass system fails and water enters reservoir exceeding capacity of spillway or storage
    or an external creek diversion failed and water entered reservoir
Pond allowed to reach crest of dam poor operations
Pond allowed to reach dam by design (discharge from top end of pond to save dam height
Excessive precipitation fills ponds exceeded storage capacity dam overtops
Water balance not maintained (human error)

Dam (upstream or downstream instability)
Seepage causes piping and removes dam material filter fails
Seepage raises pore pressures and causes instability shallow
Seepage raises pore pressures and causes instability deep
Seismic liquefaction of dams
Seismic deformation of dams
Seismic liquefaction of tailings leads to erosion
Liquefaction of tails overloaded dam
Non Seismic liquefaction of dam due to straining or increased pore pressures
Seepage failure raised pore pressures and triggered a slide includes freezing of face
Construction pore pressures raised and slope moved
Saturation of uncompacted fill either by first fill or rain or snow encapsulated in dam fill melts, dam settles, and overtops
Uncontrolled toe erosion retrogressed
Erosion on the face caused by uncontrolled precipitation or snow melt

Foundation
Karst collapse beneath dam
Collapse due to mine subsidence tails escape into mine or void
Sliding on weak soil or liner interface
Compression of weak soils led to cracking
Permafrost degradation
Construction pore pressures raised and foundation moved
Seepage through a poor membrane or pervious soils into groundwater system, bypassing seepage recovery systems
Seismic liquefaction of foundations
Seismic deformation of foundations
Non Seismic liquefaction of foundations

Structural
Piping around a culvert or decant pipe
Reclaim tower instability
Decant plugged
Pumps fail due to loss of power
Conduit failed
Landslide blocked spillway
Ice blocked spillway
Tailings distribution line burst on dam
Tailing main line bursts before reaching dam

Each of the elemental failure modes are considered to be independent. The events can therefore be combined using a system reliability model. Once the results of the probability of each of the elemental failure modes occurring is assessed using Table 3, elemental failure modes are combined using a simple user friendly software program to define the probability of occurrence of compound failure modes such as failure of a dam as a result of ditch plugging as shown on Figure 3.

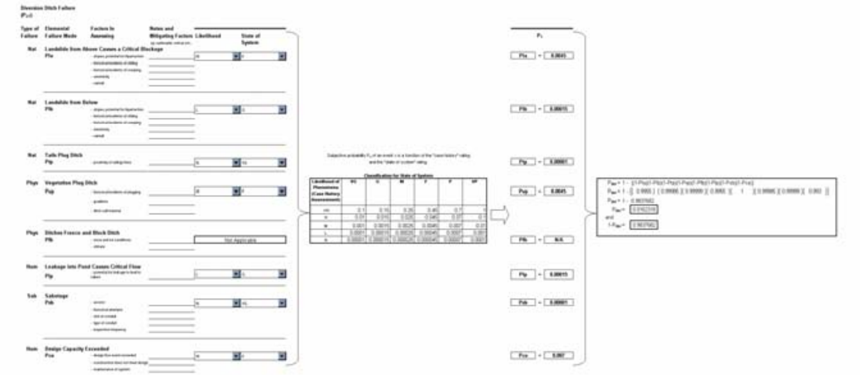

Figure 3. An example of how elemental failure modes are combined to estimate

the probability of occurrence of a compound failure mode.

The compound probability of occurrence derived from this exercise is linked to a simple event tree which to provide the probability of each of several impacts occurring. An example of the various impacts which could occur as a result of a pipe failure on top of a dam is shown on Figure 4. The probability of occurrence of each level of consequence can be estimated using simple event trees similar to that shown on Figure 5.

Table 3

Subjective probability p_x of an event x given the "case history" rating or likelihood and the "state of the system" rating.

		State of the system					
Likelihood of Phenomena (Case History Assessment)		**Very Good**	**Good**	**Moderate**	**Fair**	**Poor**	**Very Poor**
		VG	**G**	**M**	**F**	**P**	**VP**
Very High Likelihood of Occurrence	**VH**	10^{-1}	1.5 x 10^{-1}	2.5 x 10^{-1}	4.5 x 10^{-1}	7.0 x 10^{-1}	10^{-0}
High Likelihood of Occurrence	**H**	10^{-2}	1.5 x 10^{-2}	2.5 x 10^{-2}	4.5 x 10^{-2}	7.0 x 10^{-2}	10^{-1}
Moderate Likelihood of Occurrence	**M**	10^{-3}	1.5 x 10^{-3}	2.5 x 10^{-3}	4.5 x 10^{-3}	7.0 x 10^{-3}	10^{-2}
Low Likelihood of Occurrence	**L**	10^{-4}	1.5 x 10^{-4}	2.5 x 10^{-4}	4.5 x 10^{-4}	7.0 x 10^{-4}	10^{-3}
Negligible Likelihood of Occurrence	**N**	10^{-5}	1.5 x 10^{-5}	2.5 x 10^{-5}	4.5 x 10^{-5}	7.0x 10^{-5}	10^{-4}

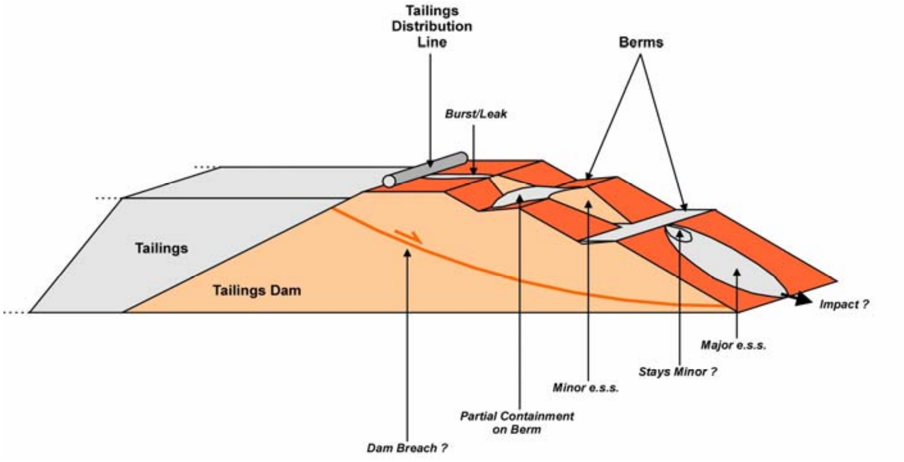

Figure 4. Typical types of imports which could occur in response to failure of a pipe on a dam.

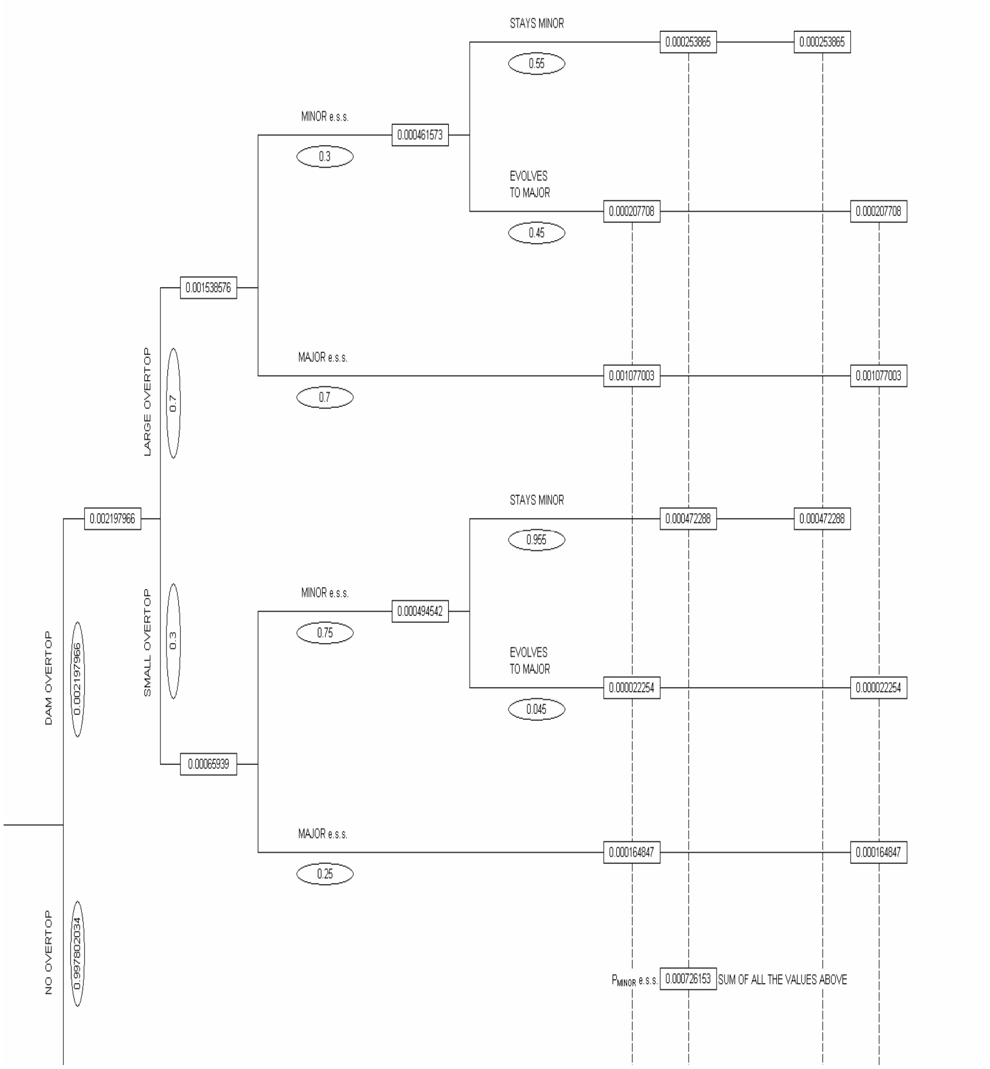

Figure 5. Simple event tree showing how the probabilities of various impacts defined on Figure 4 are estimated.

Impacts

Once the consequences are identified, the impact of each of the consequences can be assessed independently again by the local experts. The impacts are assessed in terms of clean up dollars, loss of production dollars and loss of share values as a result of bad publicity at various levels of exposure. Once the cost of an event is estimated, the quantitative value of risk can be estimated and a comparison between sites undertaken. An example of a final table allowing comparison of risk costs between mines is shown on Table 4.

Conclusions

Use of a quantitative risk assessment provides management with a decision making tool as part of a risk management program. Undertaking a user-friendly computerized program allows management and also field personnel to assess any proposed modifications, understand how the modifications can affect the risk and thereby allow them to compare directly and immediately how capital expenditures can be minimized to maximize risk reduction.

Table 4

Summary of Mine Life Risk Values

Compound Failure Scenarios	Consequence Category	Prob. Of Occurrence	Annual Prob. Of Occurrence	Cost Category	Annual Risk Units	Other Mines
Ponding on Berms Event Tree 1	P Nothing					
	P Minor ess					
	P Major ess					
	P Impact					
Distribution Line Breaks on Dam Event Tree 2	P Nothing	0.98902	0.04300	1E+02	4	3-16
	P Minor ess	0.01022	0.00044	5E+04	22	2-113
	P Major ess	0.00076	0.00003	5E+05	17	2-83
	P Impact	0.00036	0.00002	1E+06	16	9-230
Overtopping Event Tree 3	P Nothing	0.99966	0.04346	1E+02	4	3-17
	P Minor ess	0.00013	0.00001	5E+04	0	0-1
	P Major ess	0.00021	0.00001	5E+05	5	1-103
	P Impact	0.00021	0.00001	1E+06	9	9-206
Slope Instability Event Tree 4	P Nothing	0.95444	0.04150	1E+02	4	3-17
	P Minor ess	0.00957	0.00042	5E+04	21	0-21
	P Major ess	0.03599	0.00156	5E+05	782	4-782
	P Impact	0.00369	0.00016	1E+06	160	32-374
Main Tailing Line Event Tree 5	P Nothing	0.98906	0.04300	1E+02	4	2-16
	P Minor ess	0.01016	0.00044	5E+04	22	2-137

Compound Failure Scenarios	Consequence Category	Prob. Of Occurrence	Annual Prob. Of Occurrence	Cost Category	Annual Risk Units	Other Mines
	P Major ess	0.00075	0.00003	2E+05	7	2-285
	P Impact	0.00005	0.00000	1E+06	2	2-167
Polishing Pond Failure Event Tree 6	P No Impact	0.99991	0.04347	1E+02	4	3-17
	P Minor Impact	0.00002	0.00000	1E+05	0	0-3
	P Major Impact	0.00007	0.00000	1E+06	3	0-49
Mill Spill Event Tree 7	P No Impact	0.99901	0.04344	1E+02	4	3-17
	P Minor Impact	0.00025	0.00001	1E+04	0	0-426
	P Major Impact	0.00074	0.00003	5E+04	2	2-563
Probability of a Breach Occurring as a Result of Mess	P Breach	0.004440	0.0001930	1E+07	1930	53-6017

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