FAULT TREE ANALYSIS OF SLURRY AND DEWATERED TAILINGS MANAGEMENT – A FRAMEWORK

by

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Abstract

Fault trees are used in reliability and risk analysis to develop the probability of occurrence of the top event, or failure mode. The top event results from a logical sequence, or combination, of lower level events using “and” and “or” logic. Probabilities for the basic events, i.e. the lowest level events identified, are calculated or estimated in order to calculate the probability for the top event.

This thesis develops a framework for fault tree analysis for failure of alternative tailings depositional schemes (slurry, thickened, paste and filtered). Failure is narrowly defined as the release of tailings to the environment. The following failure modes are evaluated for each of the depositional schemes: overtopping, static liquefaction, internal erosion, static slope instability and seismic slope instability. The fault trees are representative of potential failure sequences in the industry as a whole and not on site-specific conditions. Expert elicitation methods are used to select the likelihoods of the basic events.

Not all events in the fault trees are applicable to the range of depositional schemes, e.g. overtopping as a result of a large pool on slurry deposited tailings management facilities is not an event that will occur for filtered tailings. The outcome is that some of the events and parts of fault trees “fall away” as the tailings solids content increases. Apart from providing a visualization of the reduction in probability of occurrence of the top events for the failure modes, the results also provide a range of probabilities for the overall probability of failure for the range of tailings management options.

The framework is used to develop a site-specific likelihood of failure of the Bafokeng tailings facility. The result demonstrates that the fault tree framework can provide useful insights in both industry-wide and site-specific tailings management facility failure likelihoods.

Preface

This thesis is original, unpublished work by the author, G. Taguchi.

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Acknowledgements

I would like to offer my cordial gratitude to my supervisor Dr. Dirk van Zyl, who has been an exceptional mentor for me and gave me a whole new perspective on mining engineering. Meeting with you is as exciting as the first time every time. I also thank Dr. Scott Dunbar and Dr. Marek Pawlik for serving as my committee members even on a tight schedule. I owe particular thanks to Mr. Jack Caldwell for constructive advice and sharing his experience as a professional engineer to enhance the quality of my thesis. My sincere thanks also goes to Dr. Wei He who helped me with static stability analysis of Bafokeng TMF. I would also like to thank ITO Foundation, who has sponsored me financially throughout my years of education. Special thanks are owed to my family, who have continuously supported me from Japan mentally even at hardship.

Dedication

This thesis is dedicated to my parents who have been my constant source of inspiration and determination. Without their love and continuous support, studying abroad and writing this thesis would not have been made possible.

To my parents

1. Introduction

The US Bureau of Reclamation and US Army Corps of Engineers have made significant progress over the last two decades on the refinement and implementation of risk-based evaluations of the facilities under their jurisdiction. These evaluations are based on event tree formulations and details are available at U.S. Department of the Interior (2013).

Throughout the 20th and so far, the 21st centuries, the international mining industry experienced a significant number of tailings facility failures that have impacted both human safety and health and the environment. Extensive research and implementation of dewatered tailings management techniques such as thickened, paste and filtered tailings have resulted in practices with many advantages over conventional slurry tailings, such as reduced water use. Table 1 summarizes the characteristics of slurry tailings and dewatered tailings. Solids contents listed in Table 1 are typical values for tailings from metal mining.

Table 1 Characteristics of tailings deposition methods

Tailings	Solids content	Conveyance system	Beach slope
Slurry	< 45%	Centrifugal pump	0.5% – 2% (Vick, 1990)
Thickened	45% – 65%	Centrifugal pump	2% – 6% (ICOLD and UNEP, 2001)
Paste	65% – 70%	Positive displacement pump	2% – 10% (Theriault et al., 2003)
Filtered	80% – 85%	Non-pumpable	No beaches

In developing conventional slurry tailings management facilities (TMFs), tailings are generally discharged from spigots installed along the embankment of the facility. For surface thickened and paste storage, tailings are discharged from a central location either through risers or from specifically selected locations as determined by site topography. Filtered tailings are generally transported by a radial conveyor stacker or by truck (Davies and Rice, 2001).

On a global basis, conventional slurry tailings facilities make up the majority of all existing TMFs. There are roughly the same numbers of thickened plus surface paste tailings and filtered tailings facilities worldwide (Davies et al., 2010; Davies, 2011).

One of the advantages of dewatered tailings management is the reduction of failure likelihood resulting from the reduction of water in the TMF. For example, overtopping resulting from a larger volume of water in conventional slurry tailings facilities is not an event that will occur for filtered tailings.

Silva, Lambe and Marr (2008) provide historic failure rates (major accidents only) of tailings facilities. They identified four categories of structures based on operations, engineering and monitoring level ranging from I (Best) to IV (Poor). For a factor of safety of 1.5, the annual probability of slope failure varies from about 0.5 to 1×10^{-6} depending on the categories. Oboni and Oboni (2013) evaluate the failure of tailings facilities internationally and in the US for a number of time periods. They found that the annual failure rates (expressed per year) for the last decade of the previous century are 2×10^{-4} worldwide and 8×10^{-4} in the US.

1.1 Research Question & Objective

The research question of this thesis is ‘Can a methodology be developed to evaluate whether dewatered TMFs have lower likelihood of failure than conventional slurry TMFs?

The objective of this research is to develop a framework for the estimation of the likelihood of failure resulting in release of tailings for different tailings depositional alternatives: slurry, thickened, paste and filtered tailings.

1.2 Thesis Outline

The next chapter provides the literature review compiling information from papers, books and websites regarding tailings, TMFs and analysis methods. In chapter 3, a framework is developed for the estimation of the likelihood of failure for different tailings depositional alternatives. The selection of failure modes is also discussed in chapter 3. Chapter 4 presents the results of fault tree analysis for selected failure modes. The results are further reviewed and analyzed in chapter 5. Chapter 6 provides the summary of this study, and recommendations for future research are given in chapter 7.

2. Literature Review

2.1 Tailings Management Options

Tailings management options can be divided into four types: conventional slurry, thickened, paste and filtered tailings. For conventional slurry storage, tailings are discharged from spigots installed along the embankment of the facility. For surface thickened and paste storage, tailings are discharged from a central location either through risers or from specifically selected locations as determined by site topography. Filtered tailings are generally transported by conveyors or truck (Davies and Rice, 2001).

On a global basis, conventional slurry tailings facilities make up the majority of all existing tailings facilities. In regard to dewatered tailings, there are roughly the same numbers of thickened/surface paste tailings facilities to filtered tailings facilities in worldwide operations. Fig. 1 taken from a recent evaluation of global trends in dewatered tailings practice presents a summary of the relative number of dewatered facilities on a global scale (Davies et al., 2010, Davies, 2011).

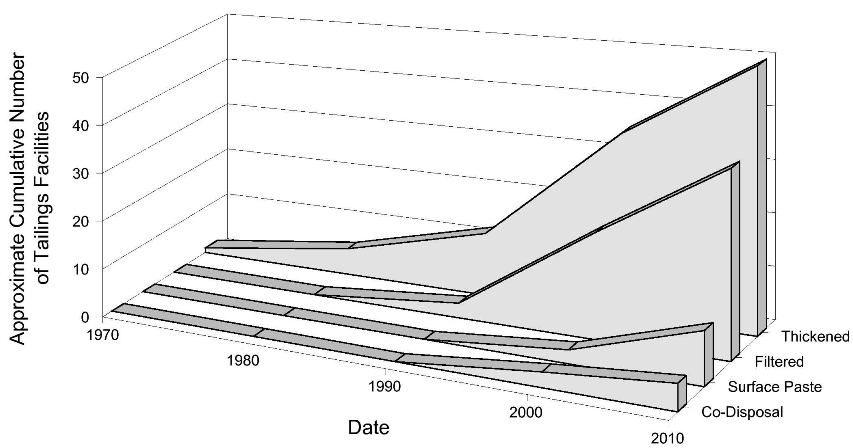


Fig. 1 Trends in use of dewatered tailings in mining (after Davies et al., 2010)

2.1.1 Tailings rheology

Rheology is the study of the flow of matter that includes liquid and soft solid materials showing plastic deformation behavior. By considering tailings rheology, it is possible to understand various tailings behaviors in a TMF.

In rheology, tailings can be classified as either Newtonian or non-Newtonian fluids. Newtonian fluids exhibit a linear relationship between the applied shear stress (τ) and the shear rate (γ) as shown in equation (1). The viscosity of fluid (η) is the ratio of the shear stress to the shear rate.

$$\tau = \eta \cdot \gamma \tag{1}$$

Non-Newtonian fluid starts flowing only when the applied shear stress exceeds the yield stress (τ_y) as expressed in equation (2).

$$\gamma = 0, \quad (\tau < \tau_y) \tag{2}$$

After the applied stress exceeds the yield stress, non-Newtonian fluids exhibit viscous liquid behavior where the viscosity is the function of the shear stress as shown in equation (3).

$$\tau = \tau_y + \eta_{(\gamma)} \cdot \gamma \quad (\tau > \tau_y) \tag{3}$$

Fig. 2 summarizes these Newtonian and non-Newtonian fluids behavior in terms of the applied shear stress and the shear rate. Curve A shows the Newtonian fluids behavior and Curve B, C and D show the non-Newtonian fluids behavior. Curve B shows a linear relationship between the applied shear stress and the shear ratio after the yield stress is exceeded. Curve C shows shear-thinning behavior where the viscosity decreases as the shear rate increases. Curve D shows shear-thickening behavior where the viscosity increases the shear rate increases.

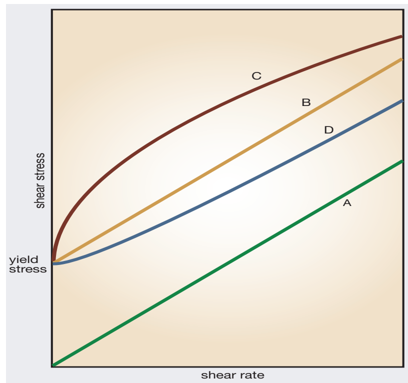


Fig. 2 **Typical flow behavior of Newtonian and non-Newtonian fluids (after Boger et al., 2006)**

The main factor affecting the yield stress of tailings and thereby differentiating Newtonian and non-Newtonian fluids is the solids content of tailings. More specifically, slurry tailings are classified as Newtonian fluids and dewatered tailings are classified as non-Newtonian fluids.

Fig. 3 shows how the yield stress of tailings increases with increasing solids content. The yield stresses and solids contents presented in Fig. 3 are the typical value for tailings from metal mining.

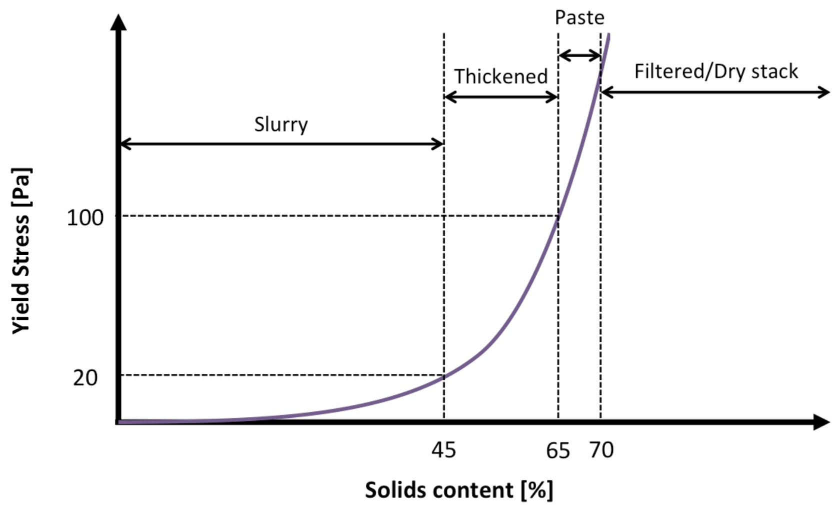


Fig. 3 Typical yield stress and solids content of tailings from metal mining

The type of tailings mineral is also the important factor affecting the yield stress and solids content. Fig. 4 presents the yield stress of various types of tailings. The relationship displayed in Fig. 3 therefore exists for each type of tailings shown in Fig. 4.

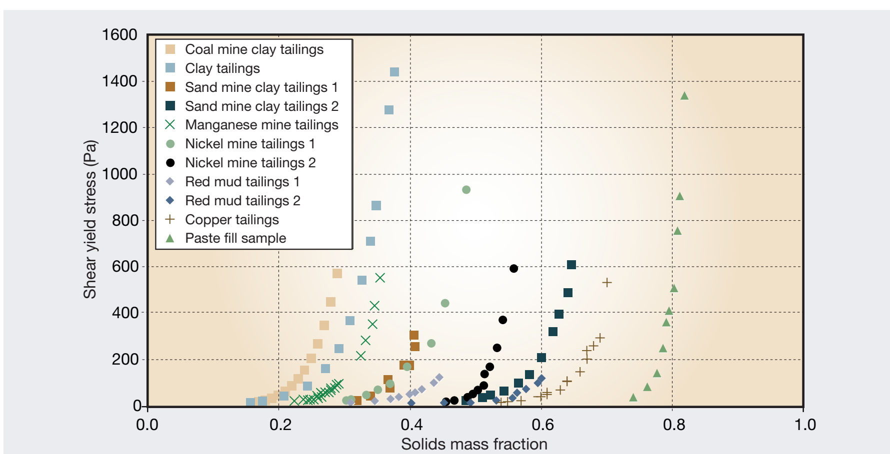


Fig. 4 Yield stress concentration data for different industry waste streams (after Boger et al., 2006)

Although there is no strict boundary between slurry and dewatered tailings, one possible practical approach is to differentiate tailings in terms of the shear yield stress. For instance, if there is a bucket of unknown tailings that have the shear yield stress of 100 Pa, it can be classified as the lower range of paste tailings.

2.1.2 Slurry tailings

Slurry tailings are the mixture of water and the residue after processing mined ores. Generally it has less than 45% solids content in hard rock mining and can be pumped from a mineral processing facility to a TMF using centrifugal pumps. Spigot disposal is normally utilized for slurry tailings. As the tailings deposit, they flow away from an outfall and natural segregation occurs, thereby creating a sloping beach between the embankment and the supernatant pond (Fig. 5). The degree of segregation depends on the particle size distribution of the tailings, the density of the slurry and the specific gravity of the particles.

The coarser (or heavier) particles of the tailings naturally settle closer to the discharge point (spigot) with the finer (or lighter) particles settling farther away. The length of beach and its slope angle are dependent on the deposition flow rate from the spigot. Mostly, the expected beach slope angle is 0.5% – 1.0% within the first several hundred feet. The higher the density of tailings becomes, the steeper the beach slope forms.

For conventional slurry tailings, multiple spigot deposition is the most common method utilized to fill a ring dyke. Spigots are installed around the perimeter of the tailings embankment and discharge tailings (Fig. 6).

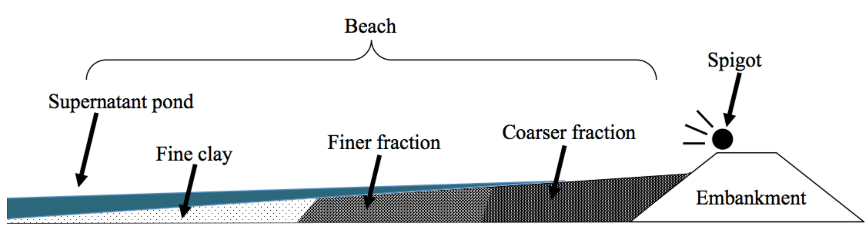


Fig. 5 Natural segregation of spigot-discharged tailings

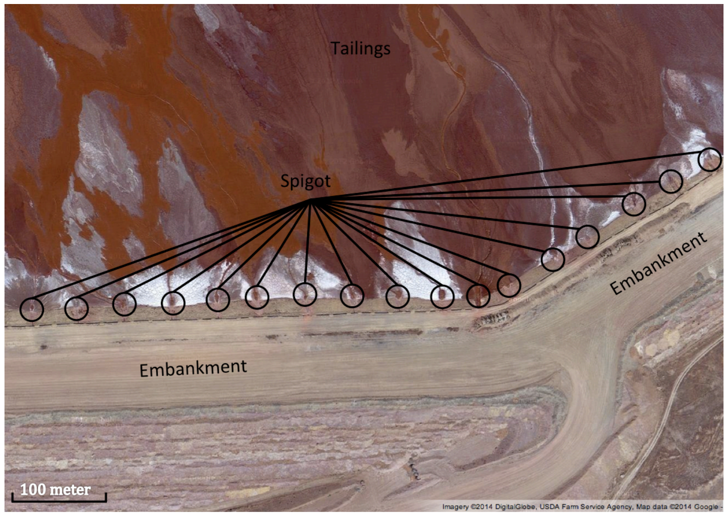


Fig. 6 Schematic diagram of multiple spigot disposal at the Twin Creeks Mine, Nevada (Original image is taken from Google Earth)

2.1.3 Thickened tailings

Thickened tailings have higher solids content than slurry tailings because of the dewatering. Its solids content ranges between 45% and 65% (typical values for tailings from metal mining), and can be transported through centrifugal pumps. Compression thickeners normally carry out the dewatering process.

Thickened tailings are typically disposed in a conical shape from the center of the cone. Higher solids content allows the construction of tailings deposit with steeper beach slope (typically 1.75% – 6%) than conventional slurry tailings, ending up with less water in the TMF. It can be dewatered to a non-segregating denser slurry that will provide for non-segregation of particles upon deposition. There is still a considerable volume of water to manage. Therefore the facilities must have an embankment at the lower end of the beach to contain bleeding water as well as surface runoff from precipitation (Fig. 7). A separate return water pond can also be established to prevent water storage on the facility.

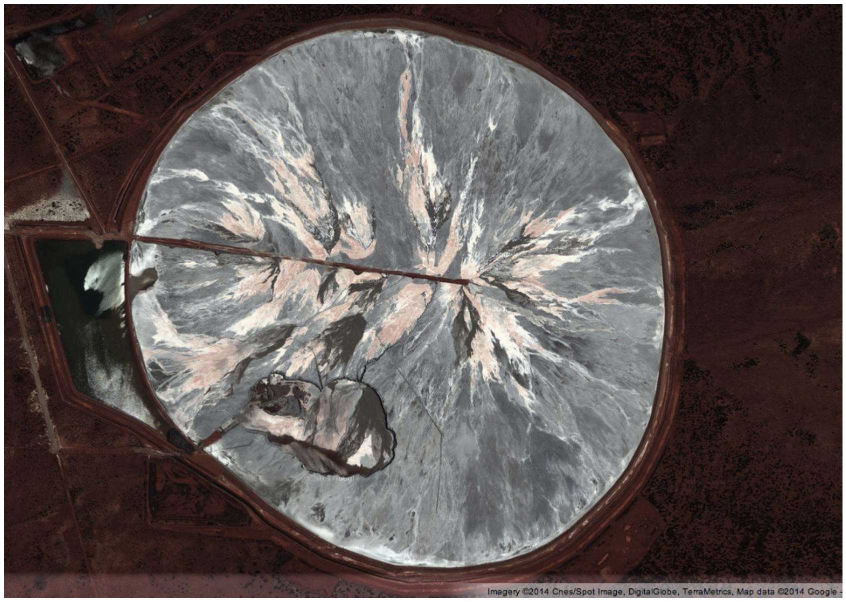


Fig. 7 Circular conical disposal of thickened tailings at Sunrise Dam Gold Mine, Australia (Original image is taken from Google Earth)

There are several advantages and disadvantages of thickened tailings from the physical, economic and environmental point of view. Firstly, the dewatering cost increases the operating cost of thickened tailings compared to traditional slurry tailings. However, thickened tailings facilities are easier to reclaim than traditional tailings impoundments, which reduces the closure cost. Second, thickened tailings form a self-supporting conical pile with relatively low retaining dykes, which reduces the capital cost. Conversely, such configuration of facility favors overtopping of the facility in case of tailings liquefaction. Static and dynamic liquefaction and adequate freeboard must be carefully assessed. Thirdly, in terms of water management, water recovery during the thickening process is the most important factor. Recovering higher volumes of water results in minimizing the seepage and evaporation loss from the tailings storage. A smaller pond than for conventional slurry tailings also reduces the potential for water to transport large volumes of tailings in case of an embankment failure. In addition, water recovery during the thickening process may represent a significant cost saving and be critical in arid regions.

2.1.4 Paste tailings

Paste tailings have higher solids content than thickened tailings. Its solids content ranges between 65% and 70% (typical values for tailings from metal mining). Tailings material dewatering takes place in high rate and deep cone thickeners. Additives (flocculants and coagulants) are typically added to the tailings to achieve higher densities. Although it has the consistency of toothpaste and is difficult to transport by using centrifugal pumps, it can still be transported through positive displacement pumps.

Similar to thickened tailings, paste tailings are deposited from a fixed location and results in a relatively steep deposit slope (typically 2% – 10%) or from a central deposition point to construct a circular conical deposit. Paste tailings are dewatered to a point where they do not segregate when deposited and ideally have minimal water bleeding when discharged. To contain bleeding water and surface runoff from precipitation, it must have an embankment at the lower end of the beach.

When it is deposited on a surface in a sub-aerial manner, like thickened tailings, desiccation and cracking may occur after deposition, increasing evaporation and speeding up consolidation. It has also been reported that "As the layers of paste cease to flow, desiccation can occur producing cracks. The new overlaying flow fills in the cracks and locks the layers together, forming a more stable structure." as shown in Fig. 8 (Tailings.info, 2013). Paste tailings management also enables a smoother transition to mine closure than traditional slurry tailings.

Fig. 8 Cracked paste and fresh paste depositing over a cracked layer (after Tailings.info, 2013)

2.1.5 Filtered tailings

Filtered tailings have higher solids content than paste tailings. Its solids content ranges between 80% and 85% (typical values for tailings from metal mining). It is produced by vacuum or pressure filtration. Gradation of particles and mineralogy of the tailings should be taken into account to achieve such high solids content/low water content. For example, high percentages of clay minerals less than 74μm hinder effective filtration or residual bitumen in oil sands tailings will also affect the performance of filtration plants (Davies and Rice, 2001).

Trafficability is typically the main issue for filtered tailings as stated by Davies and Rice (2001) "The filtered tailings are generally produced at or slightly above the optimum moisture content for compaction as determined in laboratory compaction tests (Proctor Tests). This means that a construction/operating plan is required to avoid trafficability problems. This is especially true in wetter environments since trafficability drops as moisture content rises and if the tailings surface is not managed effectively it can quickly become un-trafficable resulting in significant placement problems and increased operating costs". Filtered tailings are placed, spread and compacted to form an unsaturated, dense and self-supporting tailings stack requiring no embankment for retention (Fig. 9). Thus there is no beach unlike other types of tailings and material can be treated as an earth fill. To ensure that the land mass composed of filtered tailings is stable, it is highly recommended to compact the material by roller or truck.

Surrounding groundwater, runoff and other surface water should be diverted from the filtered tailings facility by perimeter ditches, drains and groundwater cut-off. Affected groundwater and seepage from the dry stack should be collected and might be re-used in the process. In case the groundwater has been environmentally impacted, it has to be pumped to a water treatment plant (Davies and Rice, 2001).

Economics of the dry stack management is critical to the project viability along with the filtering process. Dry stacking of tailings is relatively new technology with less experience available for the cost estimation, operation, water management and so on. High level of day-to-day management is required to achieve success.

Dry stack reclamation and closure costs are significantly lower than that for traditional slurry tailings as a result of reduced footprint and the stable surface at the end of operations. There is also a reduction in long-term risk and liability due to the absence of the tailings retention facility and the potential to impound water.

Fig. 9 Filtered tailings deposited at La Coipa Mine, Atacama, Chile (PwC, 2012)

2.2 Construction Method of Slurry TMF

TMF construction is staged over the life of the mine. For slurry tailings it begins with a starter dike constructed of natural soils or borrowed materials. Raising the embankment through subsequent lifts using tailings or borrow material is the most common construction technique. The three principal methods are to construct upstream, downstream or centerline structures, which designate the direction where the embankment crest shifts in relation to the starter dyke at the base of the embankment wall (Vick 1990).

Three sections below (Upstream construction, Downstream construction and Centerline construction) are based on Vick (1990), Martin and McRoberts (1999), Davies and Martin (2000), Davies et al. (2002) and Tailings.info (2013).

2.2.1 Upstream construction

The upstream construction method is the most economical and popular design for a tailings impoundment, mainly due to the minimal amount of borrow or other material required for construction and raising the embankment. The upstream method is also the most common design to fail, causing significant environmental consequences all over the world. There are reported to be more than 3500 TMFs worldwide, of which 50% are of the upstream design type (Davies and Martin, 2000).

Tailings are discharged by spigots or cyclones. A series of discharge points are evenly spaced along the embankment to promote laminar flow of the tailings slurry across the beach. A sequence of construction is depicted in Fig. 10.

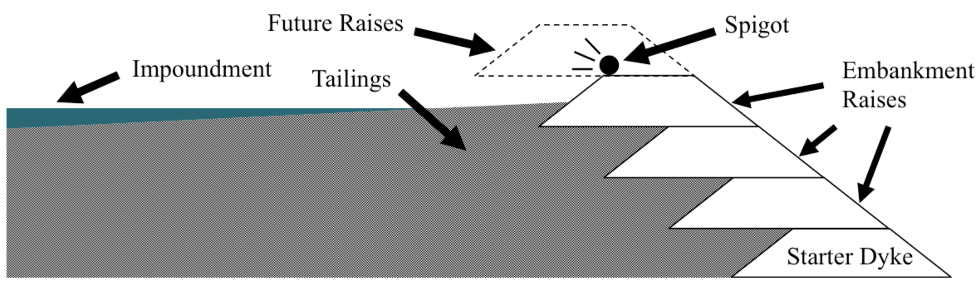


Fig. 10 Upstream construction method

A significant amount of care should be taken when raising the embankment. If the embankment is raised rapidly and the tailings under the raised embankment is not normally consolidated, pore water pressure within tailings will increase, which makes the TMF vulnerable to failure. Likewise, the impoundment and the phreatic surface need to be managed deliberately. Most failures of upstream constructed embankments occur during or after heavy rain causing water accumulation on the impoundment, which can reduce the length of the beach. Therefore upstream construction is favored in arid regions and the location where minimal amounts of water are pumped to the TMF.

2.2.2 Downstream construction

The downstream construction method is very versatile and compatible with any type of tailings. It can be used even for water storage since it can be constructed to be as robust as water-retention dams. It is therefore the most stable structure of three slurry tailings deposition options. On the other hand, it requires the greatest quantity of dam fill that increases for successive raises, especially towards the end of the mine life and is often the most costly method.

The construction of a downstream embankment starts with the construction of starter embankment. As the embankment is raised, the new wall is constructed and supported on top of the downstream slope of the pervious section, shifting the centerline of the top of the embankment downstream as the embankment stages are progressively raised (Fig. 11). An advantage of the downstream design is that the raised sections can be designed to be of variable porosity, in order to further control the phreatic surface of the TMF. Thus, downstream construction is particularly suited to areas of high seismicity. The installation of impervious cores and drainage layers will allow the facility to hold a substantial volume of water directly against the inner wall of the facility.

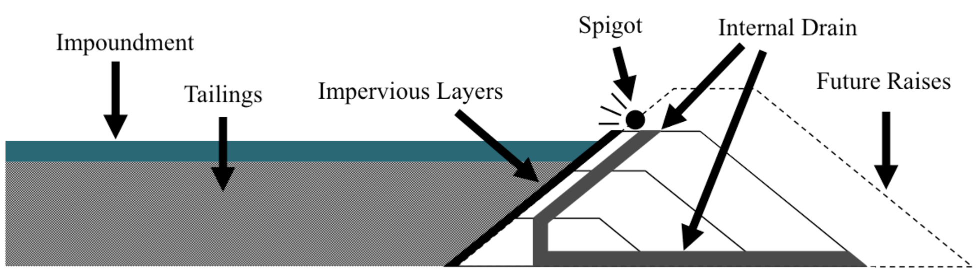


Fig. 11 Downstream construction method

2.2.3 Centerline construction

Centerline construction is a hybrid between upstream and downstream construction. The material requirements are midway between those of upstream and downstream embankments. The phreatic surface is generally low depending on the materials – careful monitoring is mandatory. The embankment has good seismic resistance and requires less fill than downstream construction.

As with upstream construction, centerline construction relies on the deposited tailings to form the main upstream support for the TMF.. The downstream zone may be constructed of conventional borrow materials or cycloned sand (McLeod et al., 2003). The design can incorporate internal drainage zones (Fig. 12). Therefore, the free water can be tolerated closer to the embankment crest than for upstream construction, without concerns of increasing the phreatic surface and causing a potential risk of failure.

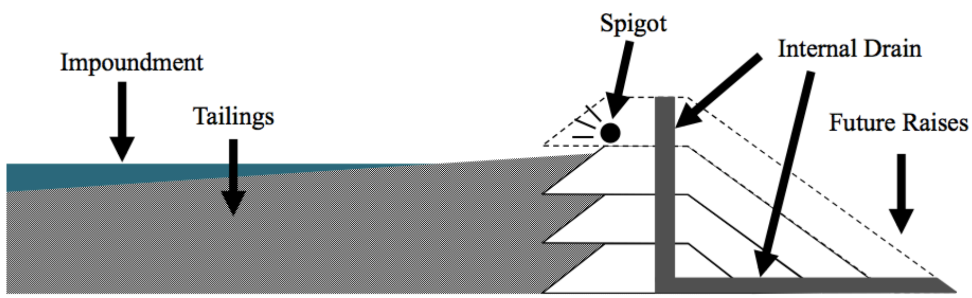


Fig. 12 Centerline construction method

2.3 TMF Failures

There are a number of failure causes of a TMF. In 2001, International Commission on Large Dams (ICOLD) performed a comprehensive study and identified 221 tailings dam incidents all over the world, which is based on the database provided by the US Commission on Large Dams (USCOLD) that collected 185 tailings dam incidents in the USA during the period 1917 – 1989. United Nations Environmental Programme (UNEP) added 26 cases to this database in 1996, and 12 examples were added by ICOLD. After some duplications were eliminated, the total number became 221. Failure statistics are presented for the following failure modes: overtopping, slope instability, earthquake, foundation, seepage, structural, erosion, mine subsidence and unknown. Furthermore the statistics also make a differentiation between failures and accidents. If a tailings facility breaches or tailings are released to the environment causing damages and troubles during operation, it is classified as a failure. Because of tailings and water existing inside of a TMF, failures generally result in catastrophic consequences. If a tailings facility breaches during or before initial filling, it is classified as an accident. Also, if some disturbances happen to a tailings facility during operation not causing any damages to the facility or being rectified before a failure occurs, it is classified as an accident.

Fig. 13 presents the statistics for causes of incidents for active and inactive tailings facilities. Tailings facilities are described as 'inactive' when an impoundment is completely filled or when tailings production ceases. The most significant causes of failure of inactive tailings facilities are overtopping and earthquake. The leading causes of incidents for active tailings facilities are slope instability, overtopping and earthquake.

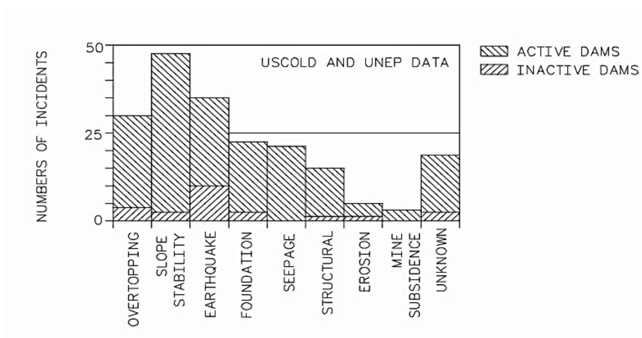


Fig. 13 Tailings dam incident cause comparison with dam status (after ICOLD and UNEP, 2001)

The incident causes for failure of active tailings facilities are shown in Fig. 14 separating failures from accidents, where it will be seen that slope instability, overtopping, earthquake and seepage cause more than or equal to 10 failures.

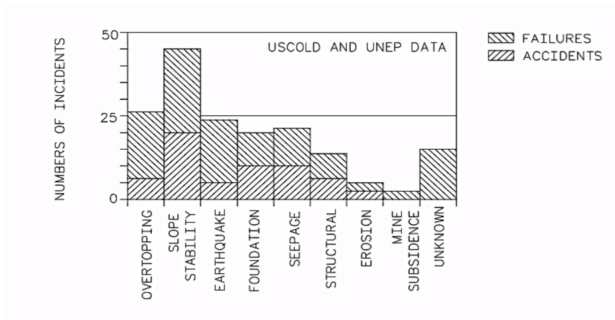


Fig. 14　Tailings dam incident cause comparison with incident type for active dams

Fig. 15 provides the total incidents with their causes with respect to tailings facility types. This figure indicates that the leading causes for incidents are slope instability, earthquake, overtopping and seepage: particularly so for upstream-constructed tailings facilities, which are the most prevalent tailings management facilities all over the world.

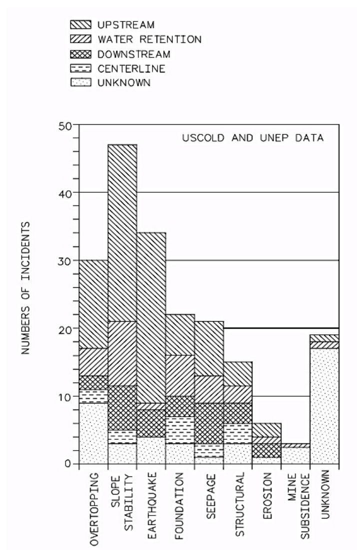


Fig. 15　Tailings dam incident cause comparison with dam type (after ICOLD and UNEP, 2001)

Rico et al. (2008) carried out a detailed search and re-evaluation of these UNEP databases in the scope of an EU project (e-EcoRisk, a regional enterprise network decision-support system for environmental risk and disaster management of large-scale industrial spills). As a result of revision, cross checking and information updating, 147 tailings dam failures in the world were identified with accuracy and 11 failure causes are listed to cover all tailings dam failures as shown in Fig. 16. Note that the failure causes listed by Rico et al (2008) overlaps with some of those listed by ICOLD and UNEP (2001), while others are different. The failure causes listed by the former are: foundation, slope instability, overtopping/overflow, mine subsidence, unusual rain, snow melt, piping/seepage, seismic liquefaction, structural, unknown, and management operation.

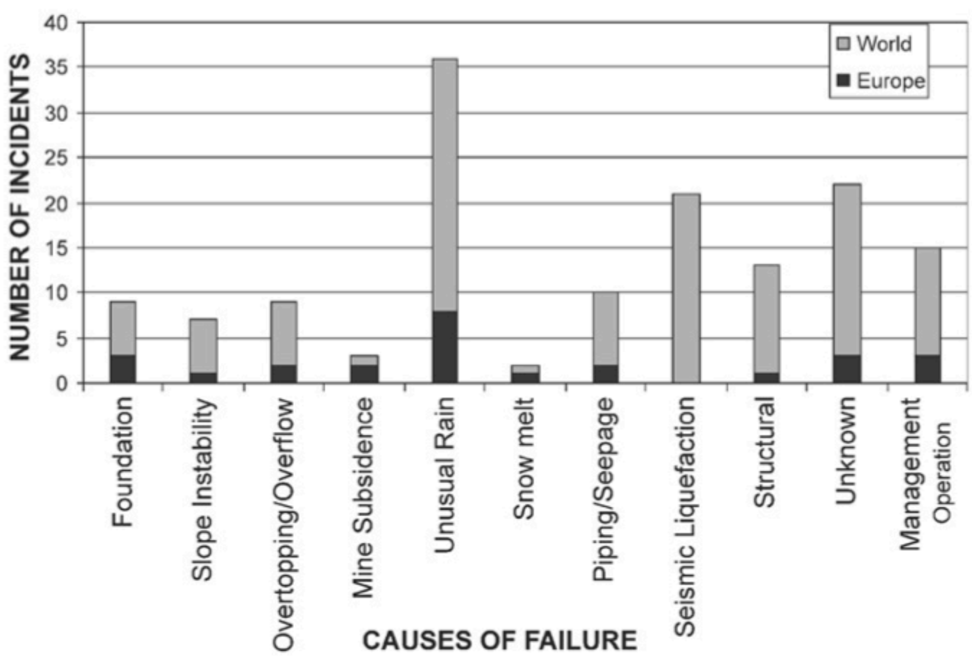


Fig. 16 Distribution of the number of incidents according to cause in the world and in Europe (after Rico et al., 2008)

2.4 Probabilistic Analysis of Tailings Management Facilities

Comprehensive studies on failure likelihood of TMFs have been conducted with different approaches. In this section, statistical event tree analyses are investigated as complementary approaches to fault tree analysis that is described in a later section.

2.4.1 Statistical analysis

Historic failure rates (major accidents only) of tailings facilities are reviewed by Silva, Lambe and Marr (2008). They propose the presentation in Fig. 17 and identified four categories of structures based on operations, engineering and monitoring level ranging from I (Best) to IV (Poor). Silva et al. (2008) presents the following four categories as they relate to types of facilities:

"Category I – facilities designed, built and operated with state-of-the-practice engineering. Generally these facilities have high failure consequences;

Category II – facilities designed, built and operated using standard engineering practice. Many ordinary facilities fall into this category;

Category III – facilities without site-specific design and sub-standard construction or operation. Temporary facilities and those with low failure consequences often fall into this category; and

Category IV – facilities with little or no engineering."

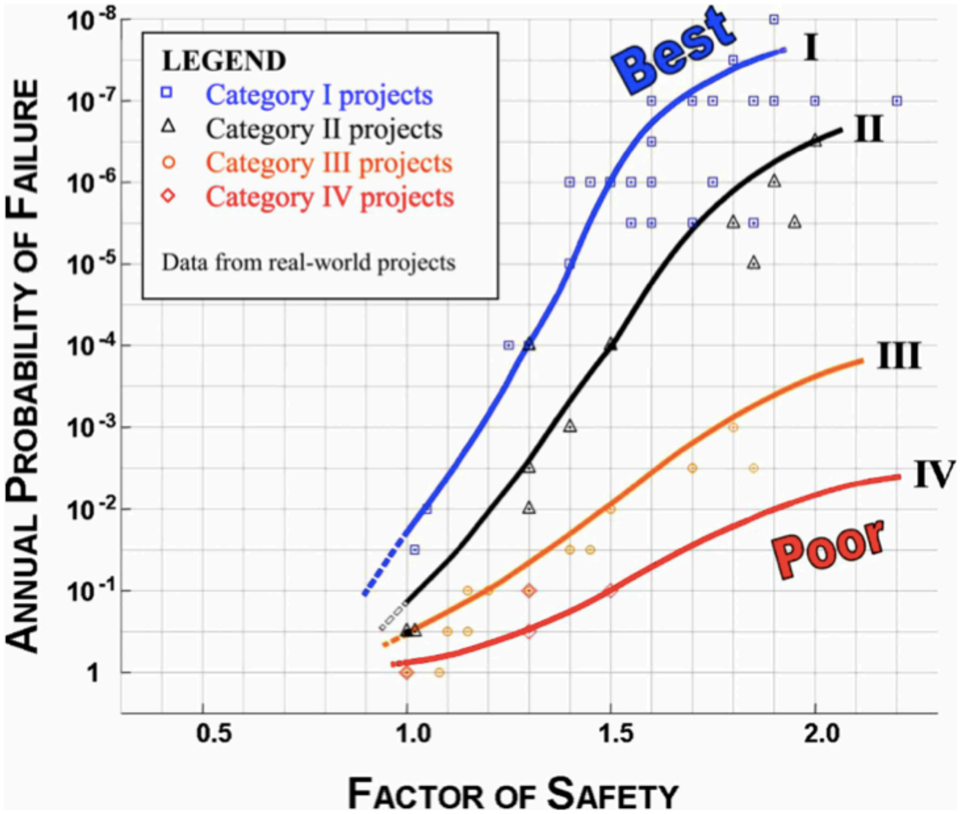


Fig. 17 Annual probability of failure vs. factor of safety following Silva, Lambe, Marr (Silva, Lambe and Marr, 2008)

Fig. 17 contains data from over 75 projects covering over 4 decades. The projects include zoned and homogeneous earth embankments, tailings embankments, natural and cut slopes, and several earth retaining structures. The authors used an iterative process to arrive at the probability of failure determinations by adopting two data points as reference points for the curves in Fig. 17. The first point is (1.5, 0.0001), which means that for the factor of safety of 1.5, the annual probability of failure is 0.0001. This is based on the historical performance of earth dams designed and constructed with conservative engineering practice. The second point is (1.0, 0.5). This point is suggested by Vick (1994) and based on the theoretical fact that a normally distributed uncertainty on factor of safety gives the annual probability of failure of 0.5 at the factor of safety of 1.0.

For the factor of safety of 1.5, the annual probability of slope failure varies from about 0.5 to 1×10^{-6} depending on the categories. (Silva, Lambe and Marr, 2008)

Oboni and Oboni (2013) evaluate the failure of tailings facilities internationally and in the US for a number of time periods. By combining USCOLD (1994), UNEP (1996, 1998) and Davies & Martin (2000) data, they found that the annual failure rates for the last decade of the previous century are 2×10^{-4} worldwide and 8×10^{-4} in the US.

2.4.2 Event tree analysis

As indicated before the US Bureau of Reclamation and US Army Corps of Engineers have refined the implementation of risk-based evaluations of water retaining dams. These evaluations are based on event tree formulations (U.S. Department of the Interior, 2013).

Event tree analysis as used by these agencies follows a failure from the initiating event, its propagation and development to the final consequence as shown in Fig. 18.

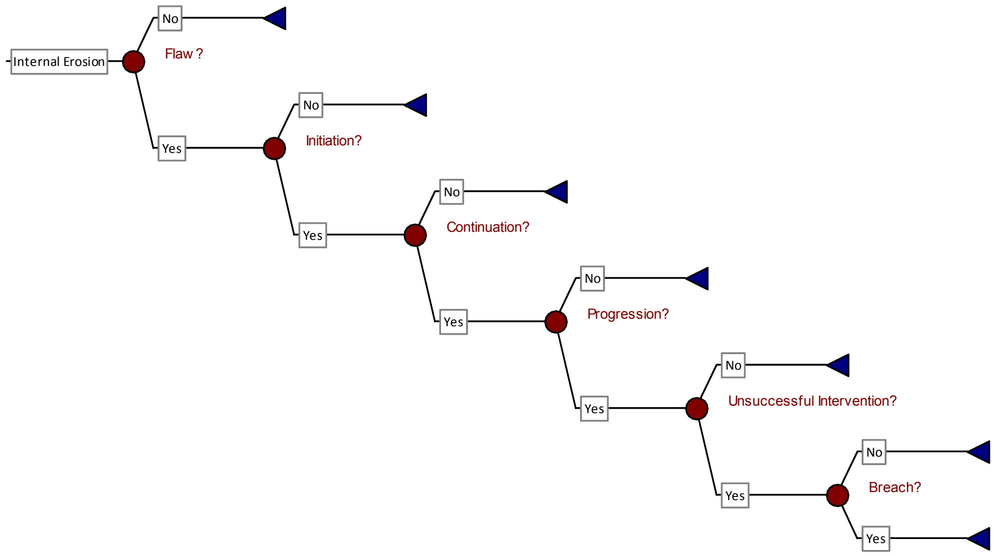


Fig. 18 Example event tree for internal erosion (after U.S. Department of the Interior, 2013)

In Fig. 18, the initiating event is internal erosion. Subsequent events are then defined using a divergent branching structure where each branch represents a unique event or state such as initiation, continuation or progression.

Event tree analysis is particularly useful when conducting complete risk assessments because it can consider the likelihood of failure events and a range of consequences.

2.5 Fault Tree Analysis

2.5.1 Overview

Fault tree analysis is a top down, graphical representation of the critical failures. The fault tree starts with some failure condition and then considers all possible chains of faults that could lead to that failure (Baecher and Christian, 2003). It is a useful tool to identify areas of concern for new system design or for improvement of existing facilities. It also helps identifying the best ways to reduce risk by correcting or mitigating problems. Fault tree analysis is a widely used method in the fields of reliability engineering to determine the likelihood of an accident or a particular functional failure.

2.5.2 Procedure

The first step in developing a fault tree is to identify a critical failure and put it at the top of the diagram. This is the 'top level' event to be investigated. Starting with the top event, the possible intermediate causes leading to the top event are identified. Each of these failures is analyzed to identify how they could be caused. Stepwise identification of undesirable system operation is followed to successively lower system levels until further analysis becomes unproductive (ISO/IEC, 2009). When drawing a tree, Boolean logic is used to combine a series of lower-level events. An example of a fault tree and conventional logic gate symbols are depicted in Fig. 19. Note that the simplified fault tree in Fig. 19 illustrates the main concepts. Some symbols typically included in fault trees for mechanical systems are not included.

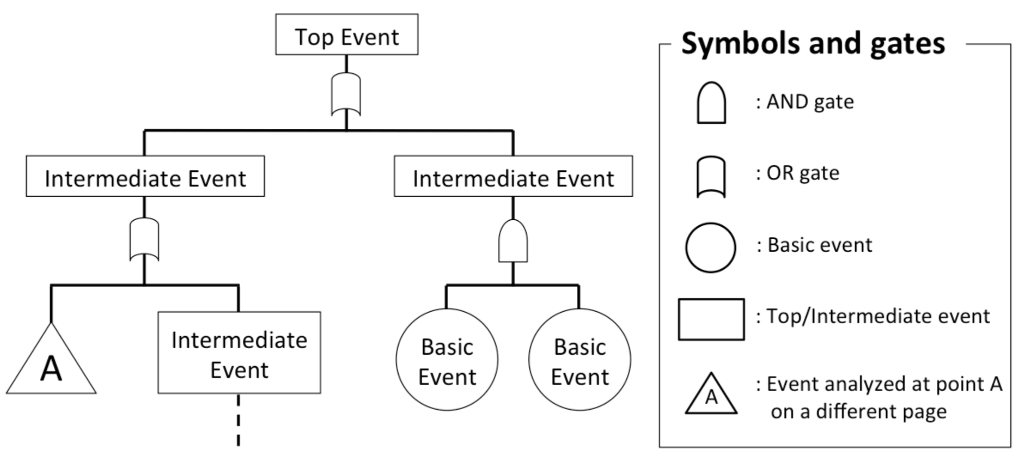


Fig. 19 Example of fault tree

Table 2 Conventional graphic symbols of fault tree

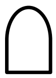
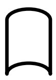
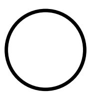
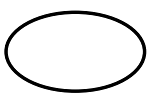
	AND gate	The higher level event occurs only if all causes occur
	OR gate	The higher level event occurs if any cause occurs
	Top level event Intermediate event	The event which needs to be explored (tree-downed) more to quantify the likelihood
 	Basic event or Root cause	Quantifiable failures or errors in a system Although it is recommended to use a circular shape for basic events, an elliptical shape is also used in this thesis because of space limitation.

Table 2 is a summary of conventional graphic symbols used in a fault tree. When there is a higher-level event (X) which occurs only if all lower-level events (say A and B) occur, the AND gate connects these events. When event A and event B are statistically independent, the probability of higher-level event (X) is

$$P(X) = P(A \cap B) = P(A) \times P(B) \tag{4}$$

When event A and event B are statistically dependent, the probability of higher-level event (X) is

$$P(X) = P(A \cap B) = P(A) \times P(B|A) \tag{5}$$

P(B|A) is called conditional probability. In this thesis, conditional probabilities are not assigned (refer to page 62). Thus, the calculation for AND gate will still be just the multiplication.

When there is a higher-level event (X) which occurs if any lower-level event (say A or B) occurs, the OR gate connects these events. Then, the probability of higher-level event (X) is

$$P(X) = P(A \cup B) = P(A) + P(B) - P(A \cap B) = P(A) + P(B) - P(A) \times P(B) \quad (6)$$

When the likelihood of lower-level event is small, the multiplication of those likelihoods (P(A) × P(B)) will be negligibly small. Therefore, equation (6) is approximated as

$$P(X) = P(A \cup B) = P(A) + P(B) - P(A) \times P(B) \approx P(A) + P(B) \quad (7)$$

For instance, if the probability of event A is 0.02 and the probability of event B is 0.01, the true value (equation (6)) is 0.0298 and the approximate (equation (7)) is 0.03. The difference is less than 1%, and thus there is no significant difference in using equation (7).

When event A and event B are statistically dependent, equation (6) and equation (7) can be written as

$$P(X) = P(A \cup B) = P(A) + P(B) - P(A \cap B) = P(A) + P(B) - P(A) \times P(B|A) \quad (8)$$

$$P(X) = P(A \cup B) = P(A) + P(B) - P(A) \times P(B|A) \approx P(A) + P(B) \quad (9)$$

A rectangular shape event symbol represents a 'top level' event or an intermediate event for which the probability cannot be calculated directly, thus requiring more breakdowns until they become an aggregation of basic events.

A circular shape event symbol represents a basic event or root cause for which probability must be quantified directly from other analysis, database or estimates.

2.6 Subjective Probabilities of Basic Events

Many important uncertainties in risk analysis are not well-adapted to quantitative estimation from data. In some instances no data is available, but only the judgment of experts. The implicit knowledge of experts is based on intuition, past experience, subjective theory, and other qualitative beliefs that are not easily amenable to mathematical representation. Yet, this judgment of experts has been an important source of information in analyzing risk. (Baecher and Christian, 2003)

2.6.1 Heuristics and bias

A great deal of experience has shown that subjective probabilities are often affected by biases and heuristics, such as overconfidence, anchoring and representativeness. For example, as to overconfidence, Fischhoff et al. (1977) conducted a range of experiments in which subjects provided answers to general-knowledge questions as well as the subjective probabilities of error only when their answers were correct. The results of experiments (Fig. 20) show their overconfidence that is expressed by the difference between actual and subjective error probabilities.

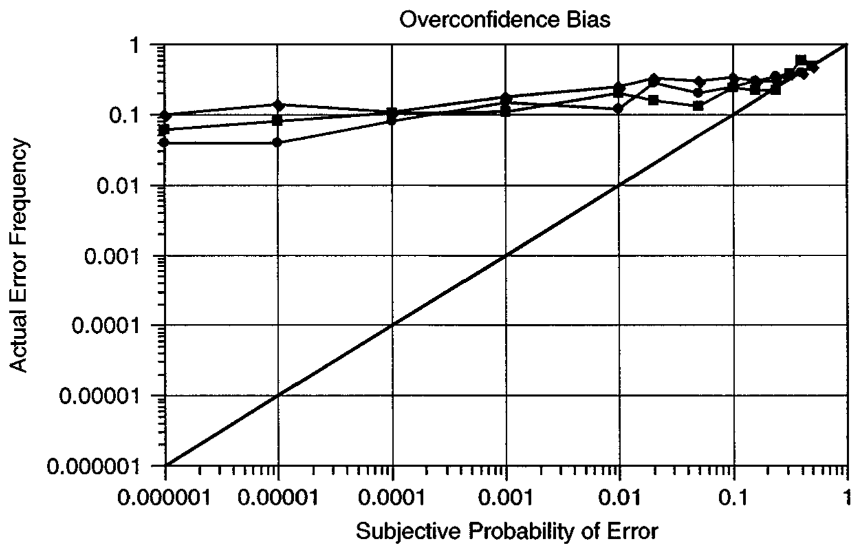


Fig. 20 Subjectively estimated vs. actual probabilities (Data from Fischhoff et al. (1977), after Vick (1997))

Folayan et al. (1970) obtained similar results on over-confidence effects from geotechnical engineers. Estimated distributions for compressibility parameters of San Francisco bay mud are provided by geotechnical engineers with up to 17 years of experience. Baecher (1972) further analyzed these prior distributions in comparison with those obtained from subsequent laboratory tests. As shown in Fig. 21, the estimated mean values are lower than that measured. However, the more significant and remarkable fact is that overconfidence produces distributions too narrow to encompass most of the measured data. The one exception is expert 5, a graduate student whose estimated distribution shows gross under-confidence.

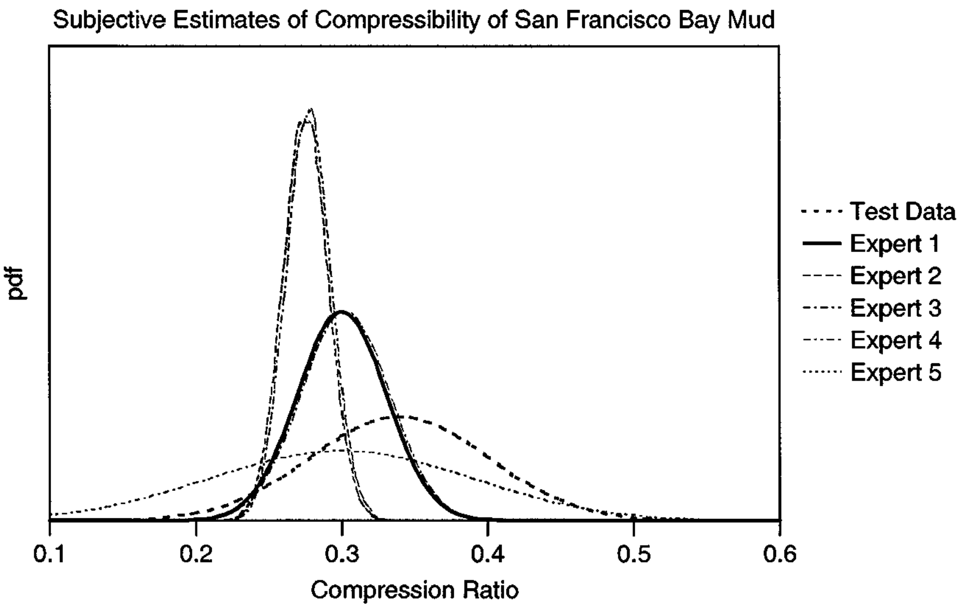


Fig. 21 Subjective estimates of the compressibility of San Francisco Bay mud compared to test results for five experts (after Folayan, J., Hoeg, K. and Benjamin, J., 1970)

As seen from the above, people including experienced geotechnical engineers are not inherently proficient at quantifying subjective probabilities, at least in the sense of providing figures that are consistent, coherent, and well calibrated. Although the effect of biases and heuristics cannot be completely removed, it could be reduced or mitigated by eliciting expert judgment (Baecher and Christian, 2003).

2.6.2 Anchoring and adjustment

Anchoring and adjustment also have been a problem in the estimation of subjective probabilities. When people are asked to estimate a value, they often begin with the best estimate and then adjust the value up or down. People are apt to stick too close to the initially estimated value and cannot adjust adequately to reflect uncertainty. This type of tendency is called ‘anchoring and adjustment’ that typically result in overconfidence in estimated distributions.

There is one well-known way to avoid ‘anchoring and adjustment’. When people are asked to estimate the undrained shear strength of soil, for example, a broader range of evaluated uncertainty and a better calibration are produced if they first state the possible largest value of the strength, then the lowest, and only afterwards focus on a central value. (Baecher and Christian, 2003)

2.6.3 Expert elicitation

In discussing expert elicitation Baecher and Christian (2003) state: “A common misconception in eliciting expert judgment is that people carry fully-formed probabilistic opinions around in their heads on almost any subject of interest and that the focus of an elicitation process is merely to access these pre-existing opinions. Actually, people do not carry fully-formed constructs around in their heads but develop them during the process of elicitation. Thus, the elicitation process needs to help experts think about uncertainty, needs to instruct and clarify common errors in how people quantify uncertainty, and needs to lay out checks and balances to improve the consistency with which probabilities are assessed.”

The steps in using expert elicitation proposed by Beacher and Chritian (2003) to quantify judgmental probabilities are:

1. Identify the general uncertainties for which the probabilities need to be assessed.
2. Select a panel of experts representing the spectrum of expertise about the identified uncertainties.
3. Decide on the specific uncertainties for which the probabilities need to be assessed.

4. Use a short training program on concepts, objectives, and methods as well as common errors that people make when attempting quantification of probabilities.
5. Next, elicit the judgmental probabilities of individual experts based on their expertise.
6. Facilitate the interaction of the experts in their evaluations.
7. Document the process and communicate the outcomes with the panel of experts.

2.6.4 Reliability modeling

Engineering models may be available or should be developed for predicting the behavior of a structure such as components of a TMF. In reliability analysis, probabilities and uncertainties are assigned to the input parameters that determine the behavior of these engineering models. With the combined use of engineering models and reliability analysis, the problem is changed from directly estimating the likelihood of failure to estimating the probabilities and uncertainties of the input parameters (Baecher and Christian, 2003).

Van Zyl et al. (1996) developed a probabilistic risk assessment for a tailings impoundment founded on paleokarst in which a fault tree and reliability models are used (Fig. 22).

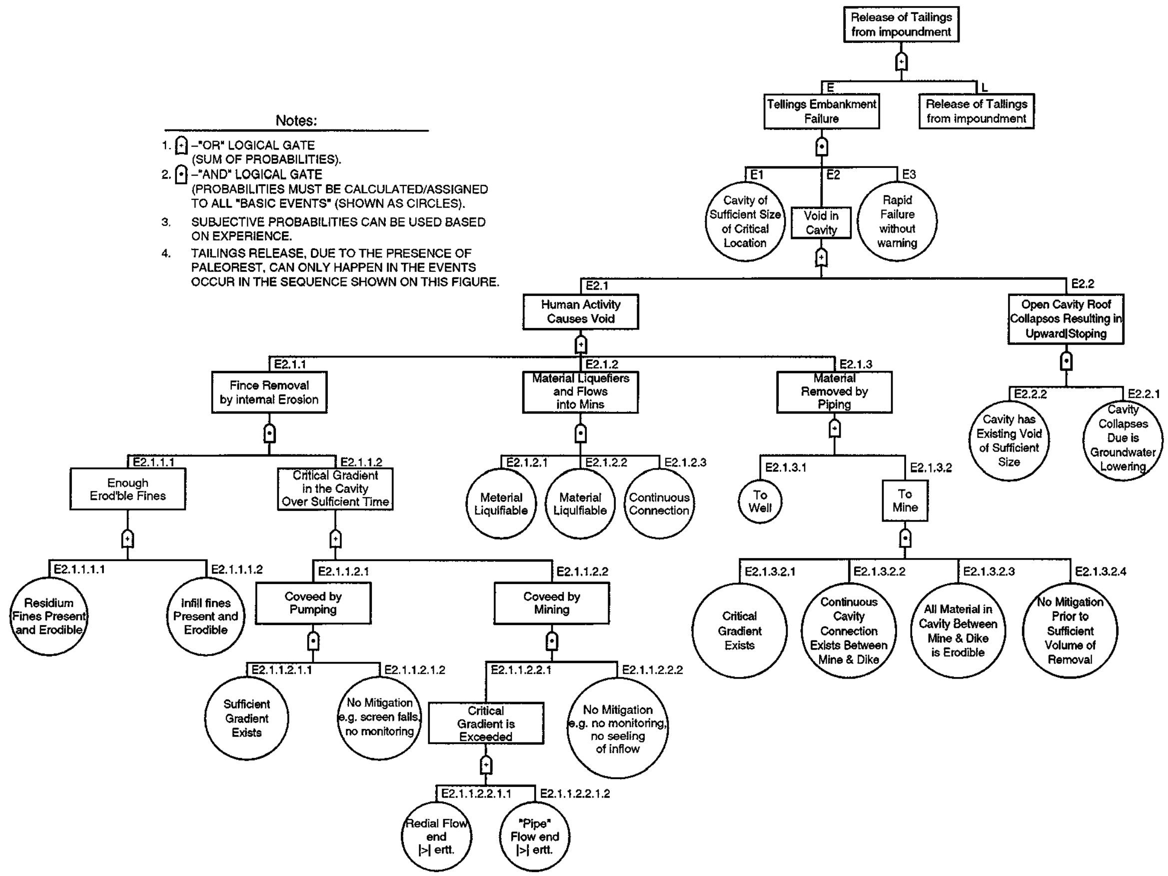


Fig.22 Fault tree for tailings embankment failure founded on paleokarst (after Van Zyl et al., 1996)

Firstly, they designed a conceptual model for limestone as shown in Fig. 23. Based on this conceptual model, they also developed reliability models for some of basic events in their fault trees. The distributions of input parameters for reliability model were obtained from site characterization drilling and the probabilities of the basic events were calculated based on the reliability model. For example, a reliability model to calculate the probability of 'Cavity of sufficient size at critical location' was presented. It was assumed that the probability of the number of cavities exceeding a critical dimension over a specific length of embankment could be determined from the binominal distribution. The main input parameters were the mean length of the cavities and the mean length of intact rock segments. These two input parameters were obtained from exploratory borehole information, shown in Fig. 24.

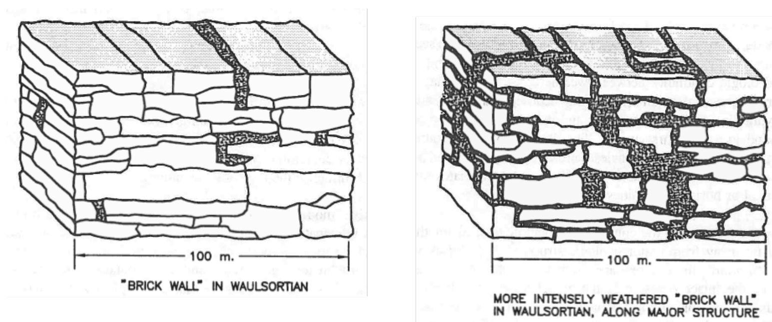


Fig. 23 Conceptual model for limestone (after Van Zyl et al., 1996)

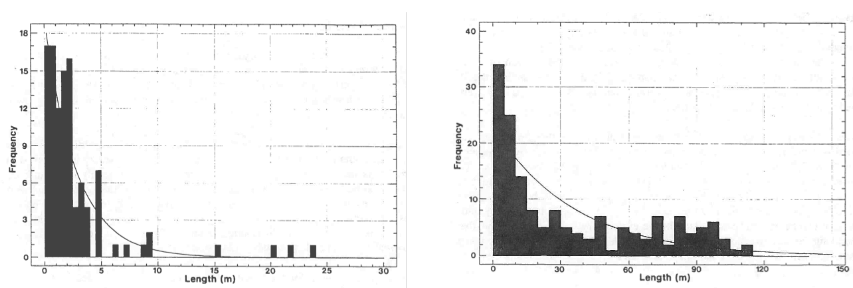


Fig. 24 Distribution of cavity length (left) and intact bedrock length (right) from exploratory boreholes (after Van Zyl et al., 1996)

The development of reliability models is only possible for site-specific conditions. These models are not simple to develop and also require site-specific information that, in most cases are costly and difficult to obtain.

3. Framework, Selection of Evaluation Method and Failure Modes

3.1 Framework

The objective of this research is to develop a framework for the estimation of the likelihood of failure for different tailings depositional alternatives: slurry, thickened, paste and filtered tailings. This framework will address the following:

- Selection of representative failure modes for the depositional alternatives
- Selection and development of the evaluation method (statistical analysis, event trees or fault trees)
- Methodology to calculate the probability of failure

This framework is not focused on site-specific conditions but on a broad view of international experiences with the design and performance of tailings depositional alternatives across the industry and many climatic regions. The outcomes can at best be very broad and only representative of the methodologies applied. This chapter of the thesis presents the development of the framework.

3.2 Selection of Evaluation Method

In Chapter 2 three probabilistic methods are described that can potentially be used in this research, namely statistical analysis, event trees and fault trees. Statistical analysis is an attractive approach as the first reaction is that it presents a useful historic perspective on TMF failures. However, the ranges of site conditions, design and operating details are not clearly defined and the statistical numbers may provide at best a broad general estimate of the site-specific likelihood of failure of a TMF. The failure analyses described in Chapter 2 did not include any dewatered tailings facilities and therefore the statistical approach will not provide any insights in probability of failure of dewatered tailings facilities.

Fig. 25 describes the difference between event tree analysis and fault tree analysis. Event tree analysis starts from the critical failure and reaches to a range of consequences. When addressing risk assessment, event tree analysis is useful because it can take into account the initial likelihood of failure and the consequences of an event. However, it does not focus on estimating the likelihood of critical failure but focuses more on how the consequences will unfold if a specific failure happens. Furthermore, the likelihood of initiating event, critical failure in this case, is often incorporated from statistical data or fault tree analysis. In contrast, fault tree analysis investigates the causes or components of the failure event. A site-specific fault tree can provide specific insights in the critical events that must be considered in design and monitoring.

In an event tree all subsequent steps are independent events effectively connecting them by 'AND' gates. Hence the likelihood of final consequence tends to be lower as the number of step increases whereas fault tree analysis can take advantage of 'AND' and 'OR' gates to evaluate the failure.

Fault tree analysis fits better into the framework for this research as it provides the opportunity to include the failure causes and mechanisms based on a broad evaluation of the industry. Fault tree analysis is therefore selected to examine how the likelihood of critical failure varies among tailings depositional methods.

The following are specific features of the fault trees:

- The overall structure of the fault tree provides insight in the range of failure causes and interactions that could occur
- Moving from slurry to dewatered tailings will not only impact the structure of the fault trees but will also change the overall probabilities of the top event occurring; this makes the fault tree a useful visual and analytical tool

- The basic events can be considered as the "critical" design and management aspects for each fault tree; they can become the focus for attention during the design and monitoring of a TMF

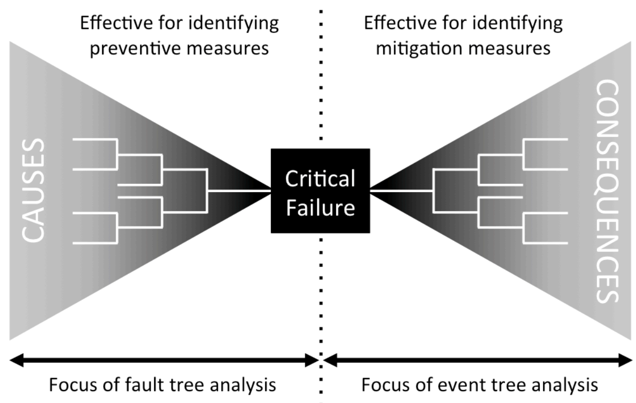


Fig. 25 Simplified graphical representation of event tree analysis and fault tree analysis (made by the author based on RRC, 2013)

3.3 Failure Modes

It is recognized that on a site specific basis there can be many causes for tailings failure, which can span the range of physical, chemical, biological and human failure. In this thesis only physical failures leading to release of tailings to the environment are considered.

The following 5 failure modes are proposed for this evaluation based on review of the literature and the evaluations below: overtopping, static liquefaction, internal erosion, static slope instability and seismic slope instability.

U.S. Department of the Interior (2013) has very comprehensive risk analysis reports on failure modes of water retention dams. Fig. 26 shows the list of these reports excerpted from their website and failure modes they cover in these reports. They covered overtopping, internal erosion, static slope instability for various types of water retention dams. Seismic slope instability and a number of structural failure causes are also evaluated. Since their focus is on water retention dams, some failure modes only true for water retention dams are covered in their reports such as trunnion friction radial gate failure. Those failure modes are generally classified as structural failure in Fig. 26 and not selected as the representative failure modes for TMFs. Although static liquefaction is not covered in their reports because water retention dams are basically well-compacted structures with high level of engineering controls, it has been a big concern for tailings facilities for a long time. Thus static liquefaction is added to the above four failure modes, and eventually 5 representative failure modes are selected for tailings management facilities

15	Erosion of Rock and Soil Presentation	- **Overtopping**
16	Flood Overtopping Failure of Dams Presentation	- **Overtopping**
17 & 18	17 - Seismic Spillway Pier Failure 18 - Seismic Failure of Walls Presentation	- Seismic and Structural - **Seismic slope instability**
19	Buttress Dams Presentation	- **Static slope instability**
20	Concrete Gravity Structures Presentation	- **Static slope instability**
21	Arch Dams Presentation	- **Static slope instability**
22 & 23	Stagnation Pressure Failure Cavitation Induced Failure Presentation	- Structural
24	Overtopping of Walls and Stilling Basin Failure Presentation	- **Overtopping**
25	Levee Floodwalls Presentation	- **Static slope instability**
26	Internal Erosion Presentation	- **Internal erosion**
27	Seismic Embankment Presentation	- **Seismic slope instability**
28	Landslides Presentation	- **Overtopping**
29, 30, and 31	29 - Seismic Failure of Spillway Radial Gates 30 - Trunnion Friction Radial Gate Failure 31 - Drum Gates and Other Gates Presentation	- Seismic and Structural - Structural
32	Mechanical and Electrical Systems Presentation	- Structural
33	Operational Failure Presentation	- Operational

Fig. 26 Risk analysis reports provided by U.S. Bureau of Reclamation (excerpted from U.S. Department of the Interior, Bureau of Reclamation's website)

In Chapter 2 (Fig. 13 to Fig. 16) the results of the tailings failure analysis provided by UNEP (2001) and Rico, et al (2008) are presented. However, they list failure causes that trigger failure modes leading to failure; this hierarchy is shown in Fig. 27. To show that those failure causes are included in the selected representative failure modes, the compilation of failure causes into failure modes is attempted.

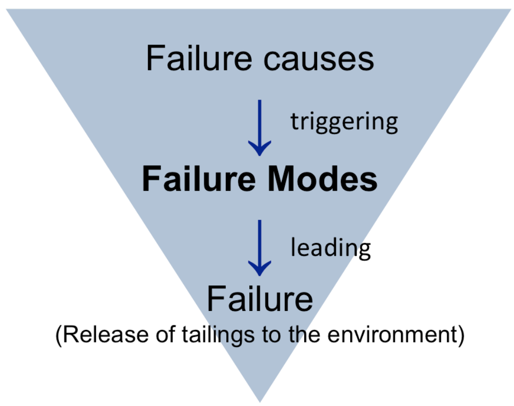


Fig. 27 Relationship between failure causes, failure modes and failure

In Fig. 28 the 8 failure causes of UNEP are represented in terms of the 5 proposed above. Mine subsidence, erosion and earthquake are considered to be failure causes triggering a sequence of events leading to failure rather than directly leading to failure. Overtopping and slope instability are considered to be failure modes since these two can directly result in the failure of a TMF. 'Foundation' and 'Structural' failure are interpreted as aggregation of failure causes, such as cracks in foundation or spillway failure, resulting in different failure modes. Seepage is interpreted as internal erosion.

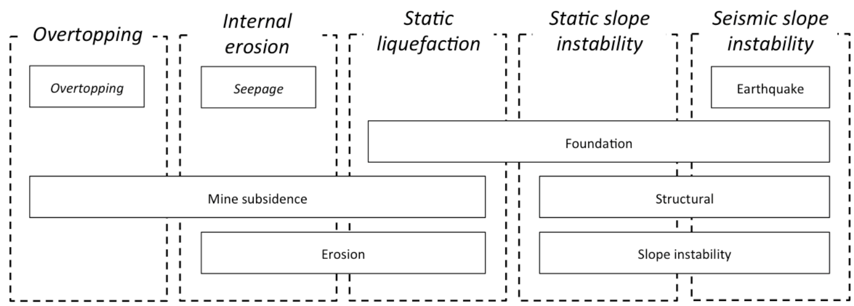


Fig. 28 Compilation of 8 failure causes from ICOLD and UNEP (2001) into 5 failure modes

Fig. 29 shows a similar compilation for the 11 failure causes of Rico, et al (2008) are represented in terms of the 5 failure modes. Unusual rain, snow melt, mine subsidence and management operation are considered to be failure causes that initiate a string of failure. Overtopping and slope instability are considered to be failure modes that can directly result in failure. The categories ‘Foundation’ and ‘Structural’ can be various failure causes rather than failure modes. Piping/Seepage is interpreted as internal erosion, while seismic liquefaction is included in seismic slope instability.

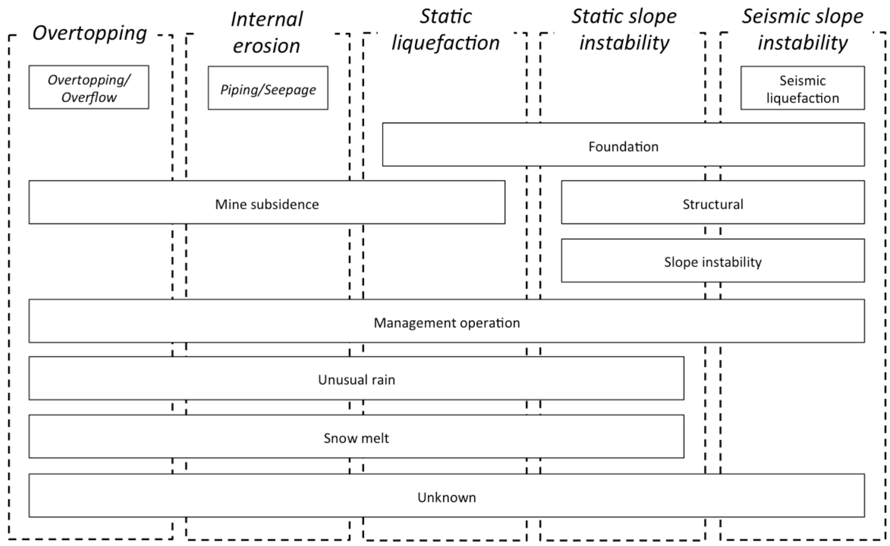


Fig. 29 Compilation of 11 failure causes from Rico et al. (2008) into 5 failure modes

It is possible to select different failure modes or add/remove some failure modes from these 5 failure modes for specific site conditions. However, the purpose of this research is not to cover 100 percent of all TMF failures but to develop a framework based on an understanding of the mechanisms. These 5 failure modes are considered to have distinguishably different mechanisms that can occur and that they are collectively exhaustive enough to cover almost all of the TMF failures, thereby helping to understand how the likelihood of TMF failure will change among different tailings.

The compilations in Fig. 28 and Fig. 29 confirm that the 5 failure modes selected for this research are representative of physical failures observed and previously identified and evaluated for tailings impoundments.

The following sections provide further descriptions of these failure modes.

3.3.1 Overtopping

Overtopping can be divided into two major failure modes: sustained overtopping and wave overtopping (Fig. 30). Sustained overtopping can occur due to water level increase in the TMF, and wave overtopping can occur due to waves washing over the crest. Water level increase until exceeding the dam crest can be caused by crest erosion, crest subsidence, poor pool management or major climatic events. Overtopping from waves normally results from strong wind, earth/rock slide into the reservoir or design error. In general, sustained overtopping results in more catastrophic failure than wave overtopping.

Overtopping is often associated with climatic events such as heavy rainfall, rapid thaw or ice blockage of spillway. For example, Merriespruit Mine in South Africa failed because of overtopping in 1994. During the evening on Feb 22nd, heavy rainfall caused an increase in the water surface elevation on the impoundment. Although personnel from the mine tried to release water through spillways and warn people living close to the mine, the high phreatic surface led to the breach of the dam. 2.5 Mt tailings were released in this incident and traveled 2,000 meters, killing 17 people. Another example is the Silver King Mine failure in 1974. On Jan 16th, rain on heavy snowpack caused the impoundment to fill to capacity, and emergency pumping was insufficient to prevent overtopping with the loss of 2 million gallons of water and 6,000 m^3 of tailings. (ICOLD and UNEP, 2001).

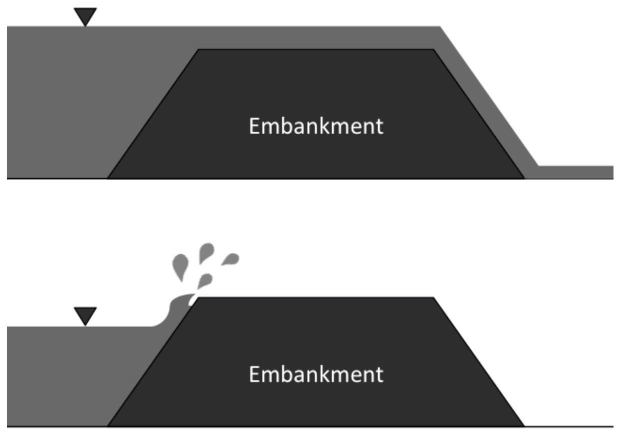


Fig. 30 Schematic diagram of sustained overtopping and wave overtopping

3.3.2 Static liquefaction

Static liquefaction or flow liquefaction refers to the process whereby a saturated or partially saturated and contractive soil loses its strength in response to an applied static stress. Static liquefaction can undermine the stability of a TMF, thereby leading to the release of tailings to the environment.

In order for static liquefaction to happen, the static shear stress must exceed the minimum liquefied undrained shear strength as can occur in the case of undrained loading of contractive material. When undrained shear stress is applied, a contractive material undergoes strain softening during which the shear stress reduces under continuous shear strains. Thus, if a triggering event places a large enough undrained stress on a TMF containing contractive materials, the shear strength will be reduced until it falls below the static shear stress resulting in static liquefaction. Fig. 34 (described below) further clarifies the process of strain softening response during undrained loading.

It is critically important to know whether materials comprising a TMF are contractive or dilative under shear stress. The critical state locus (CSL) shown in Fig. 28 can be obtained from laboratory testing while the state parameter Ψ is a theoretically sound index of material behavior and can be readily interpreted from a cone penetration test. The state parameter depends on both the density and confining stress of the soil, since it is a measure of the void ratio difference from the CSL as depicted in Fig. 31. The CSL serves as a reference state – representing the state where a soil will continue to shear under constant stress and constant volume conditions. When a soil is sheared, loose sands contract and dense sands dilate towards the critical state condition at large shear strains, with Ψ providing a measure of dilatancy (Been et al., 2012). The void ratio where the change in volume of specimen remains constant during shearing is called "critical void ratio" represented as e_c in Fig. 31.

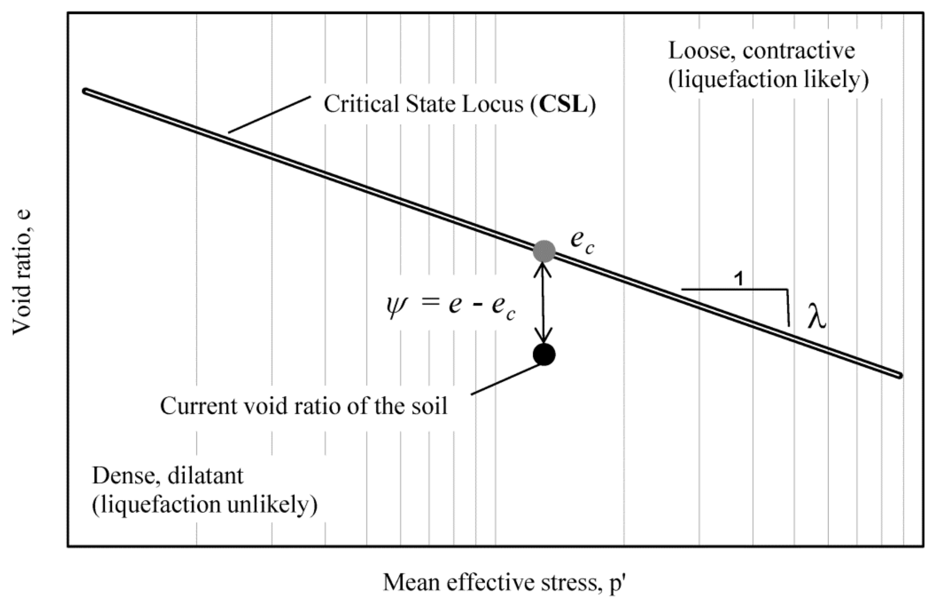


Fig. 31 Definition of state parameter, Ψ (after Been et al., 2012)

3.3.3 Internal erosion

Internal erosion is soil particle movement by water flow within a TMF. Potential failure modes for internal erosion can be classified into general categories with respect to the physical location of the internal erosion pathway

(U.S. Department of the Interior, 2013). Internal erosion can take place in an embankment, foundation or contact area between embankment and foundation. In any case, hydraulic gradient and specific material susceptibility such as plasticity, dispersiveness and particle gradation play a critical role.

The process of internal erosion can be broken into 2 phases: initiation and progression.

Garner and Fannin (2010) developed a Venn diagram to describe how internal erosion initiates as shown in Fig. 32 below. Initiation process starts where 1) material susceptibility; 2) critical stress condition; 3) critical hydraulic load are present. These three conditions are described by U.S. Department of the Interior (2013) as follows: "Material susceptibility is the relative erosion resistance (plasticity) and dispersiveness of a soil. The critical hydraulic load is related to the hydraulic energy required to invoke a mechanism of internal erosion, by means of seepage flow through the dam. In other words, this factor relates to the seepage gradients and velocities present in the embankment or foundation and whether they are sufficient to induce particle movement. The critical stress condition is related to the inability to resist internal erosion due to the magnitude of effective stress, with recognition that stress varies spatially and/or temporally within the body of the dam."

Even if internal erosion initiates, it will not progress as long as a TMF has an adequate filter based on appropriate criteria. Without an adequate filter and successful intervention, the probability of progression is virtually certain. From where initiation starts, it could progress by forming a roof and concentrated leak, which could lead to breaching of a TMF.

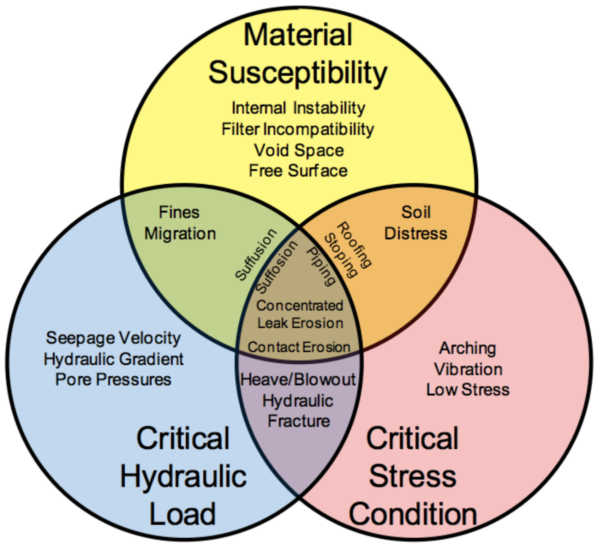


Fig. 32 Factors affecting the initiation of internal erosion (after Garner and Fannin, 2010)

Thus, the fault tree for internal erosion is constructed in terms of three factors listed in Fig. 32 and where internal erosion initiates and progresses.

3.3.4 Static slope instability

Static slope failure happens when the imposed stress on the embankment or foundation exceeds their effective strength. Two main factors affecting the static stability of slope are the shear strength of tailings and pore pressure.

The shear strength of tailings increases as the density of the tailings increases. Higher density can be achieved by densification, natural evaporation, and consolidation after deposition. Over consolidated tailings have lower void ratio and thus show dilative behavior when sheared.. Compaction of tailings after deposition has a large influence on the stability of embankment slope.

The location of the phreatic surface in a TMF is also an important factor for static slope instability, pore pressure increases as phreatic surface rises.

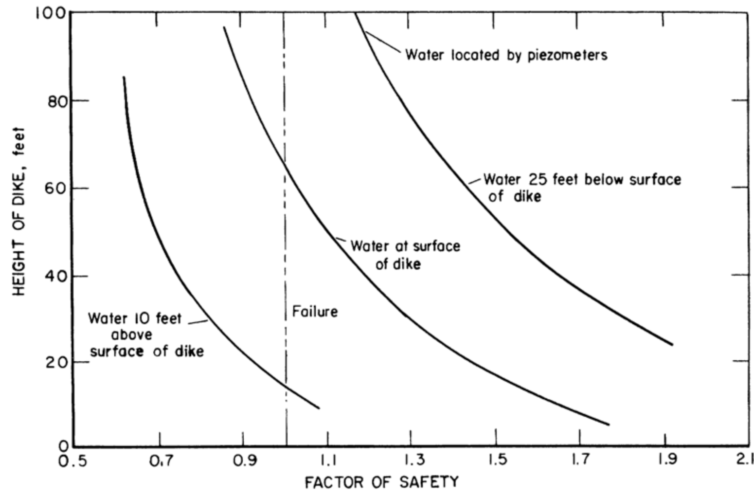


Fig. 33 Factor of safety relative to the piezometric height in dam (after Kealy and Busch, 1971)

Fig. 33 illustrates the relationship between the factor of safety and the height of dyke with the height of piezometric water surface relative to the embankment surface. The rise of piezometric head drastically reduces the factor of safety (Kealy and Busch, 1971).

The compaction of tailings is readily applicable to dewatered tailings. Therefore, the likelihood of static slope stability for dewatered, especially filtered tailings, will be lower than for slurry tailings.

3.3.5 Seismic slope instability

Seismic slope instability is a failure mode that occurs under cyclic loading from an earthquake or other seismic loading. Fig. 34 schematically presents the behavior of saturated, contractive, sandy soil during undrained loading (Olson and Stark, 2003). It depicts how the contractive soil loses its strength under static or cyclic loading and finally reaches the "liquefied shear strength" represented as s_u(LIQ) in Fig. 34.

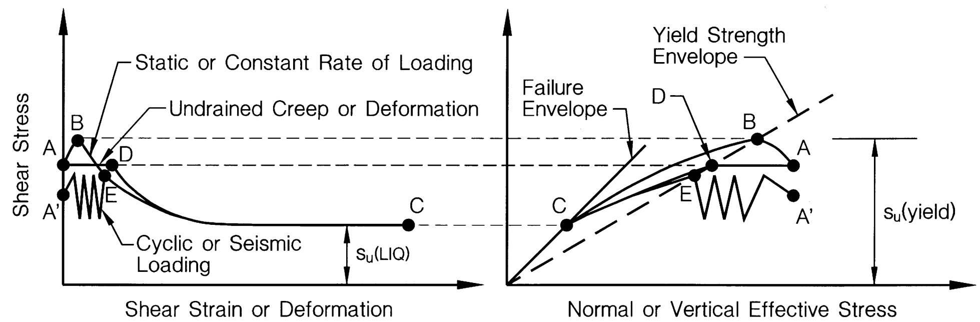


Fig. 34 Schematic undrained response of a saturated, contractive sandy soil (after Olson and Stark, 2003)

Under cyclic loads, strength decreases of a TMF and stress increases happen at the same time. The extent of strength decrease and stress increase depends on the characteristics of materials in a TMF. For example, loose soils are mostly contractive under undrained cyclic loads, which leads to pore pressure increase and finally causes seismic slope instability. Aside from the characteristics of material, size and duration of cyclic loads are also a predominant factor. Thus, it is reasonable to consider size and duration of cyclic loads and material susceptibility to seismic slope instability when analyzing the seismic reliability of a TMF.

There are four sub-failure causes that can lead to seismic slope instability: seismic liquefaction, surficial deformation, slope failure and overtopping. Seismic liquefaction is caused by strain softening response of tailings under cyclic loads as explained above. Surficial deformation can happen when surface movement caused by an earthquake near a TMF exceeds the designed distance. Slope failure occurs when the total stress (cyclic loads plus static loads) imposed on a TMF exceeds the effective strength of a TMF. Overtopping results from crest subsidence and Seiche induced by an earthquake. Although TMFs are designed, constructed and operated on the assumption of probable maximum earthquake (PME), seismic slope instability happens when the magnitude of earthquake exceeds PME.

4. Fault Trees

Fault trees are developed in this chapter for each of the failure modes selected for this evaluation, i.e overtopping, static liquefaction, internal erosion, static slope instability, seismic slope instability. These fault trees are in a broad sense representative of international practices and experiences and may be considered generic in nature. They do not reflect any site-specific conditions but integrates experiences at many different sites. Project-specific conditions will result in much different fault trees, and also potentially different combinations of failure modes and pathways than selected here (Van Zyl et al., 1996).

Fig. 35 shows the fault tree combining the separate failure modes when 'top level' failure is defined as 'release of tailings to the environment'. Fault trees for each failure mode are subsequently presented in Fig. 36 to Fig. 41. Note that the fault tree in Fig. 38 is a continuation of that in Fig. 37. In this thesis, the volume of released tailings is not addressed because it is not the cause but the consequence of failure. Even though the probability of 1 m^3 of tailings release and 1 million m^3 of tailings release might be different, the structure of fault tree would be still the same. Thus, it should be noted that these fault trees could be used to estimate the likelihood even when dealing with the amount of released tailings, however the likelihood of the basic events may be different. However, it is not further analyzed here because that is not the purpose of this research.

As the basic structures of fault trees are considered to be the same among different TMFs (upstream/centerline/downstream constructed slurry, and dewatered TMF), failure modes may have different likelihoods for different TMFs due to "removal" of some of the failure causes and mechanisms. To visualize those differences, events that are eliminated from the fault tree for dewatered tailings management facilities are shaded. For example, all the boxes of Fig. 36 (fault tree for overtopping) are shaded indicating that these causes and mechanisms do not occur for dewatered tailings. This assumes that there is not large variability of solids content delivered to the dewatered tailings facilities. In the case of large variability, the fault tree may have to be revised or the likelihoods of basic events will have to be re-evaluated.

The author and his adviser, Dirk van Zyl, reviewed the structures of the fault trees and further advice was also solicited from Mr. Jack Caldwell, Robertson GeoConsultants, Vancouver, BC.

4.1 Assigning Likelihoods for Basic Events

As noted above, the framework for this research is based on a broad view of international experiences with the design and performance of tailings depositional alternatives across the industry and many climatic regions. The likelihoods of occurrence of basic events cannot be "calculated" based on probabilistic models of site-specific conditions. It was therefore decided to use a form of expert elicitation in assigning likelihoods of occurrence to these basic events. The values were discussed between the author and his adviser (Dr. Dirk van Zyl) and further advice was also solicited from Mr. Jack Caldwell, Robertson GeoConsultants, Vancouver, BC. The experience and engineering judgment of these individuals was the basis for assigning the likelihoods.

Table 3 summarizes the probabilities and remarks of each basic failure event contained in the fault trees. These probabilities are considered to be for a generic slurry TMF with upstream construction representative of the international mining industry.

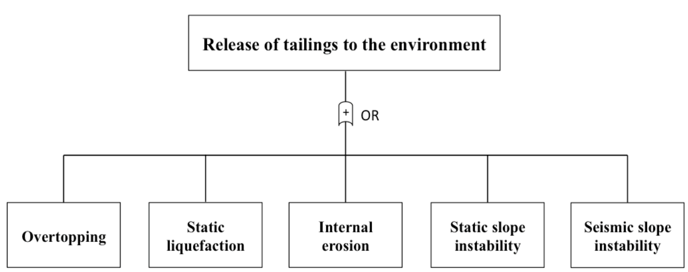


Fig. 35 Fault tree for the release of tailings to the environment

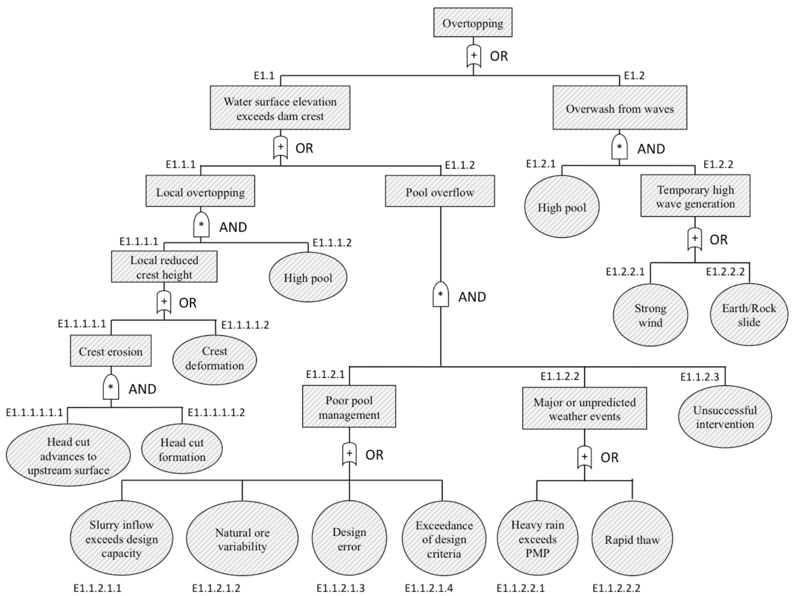


Fig. 36 Fault tree for overtopping

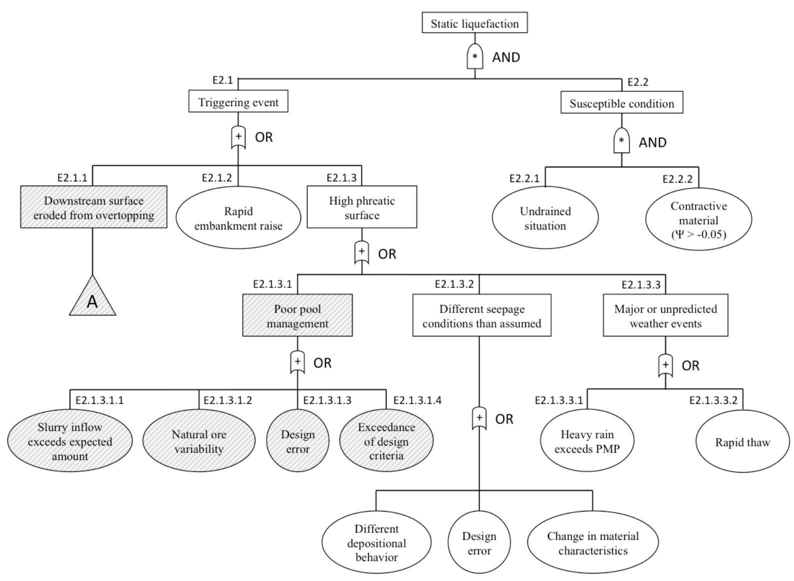


Fig. 37 Fault tree for static liquefaction

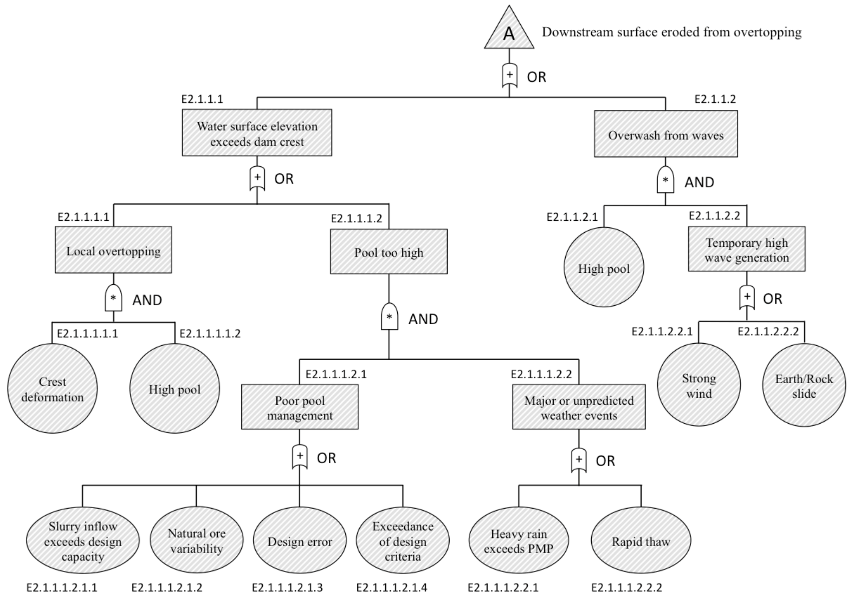


Fig. 38 Fault tree for downstream surface eroded from overtopping

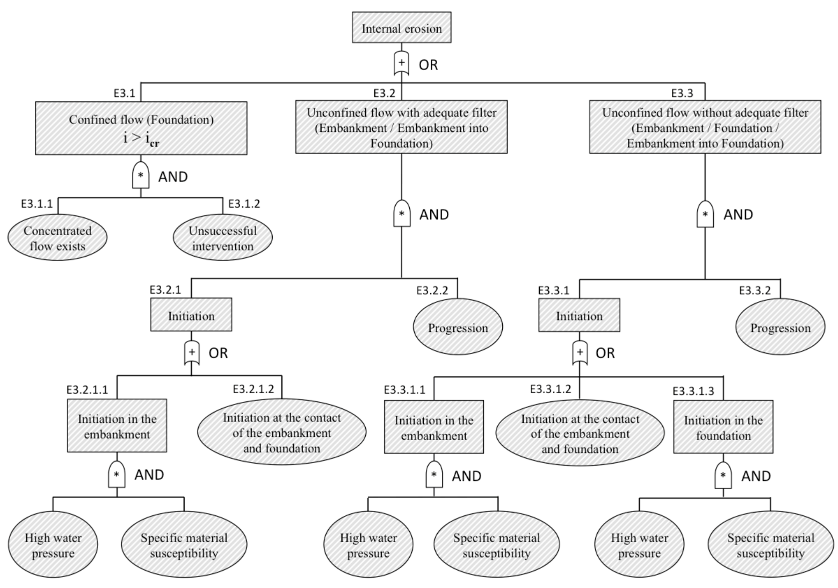


Fig. 39 Fault tree for internal erosion

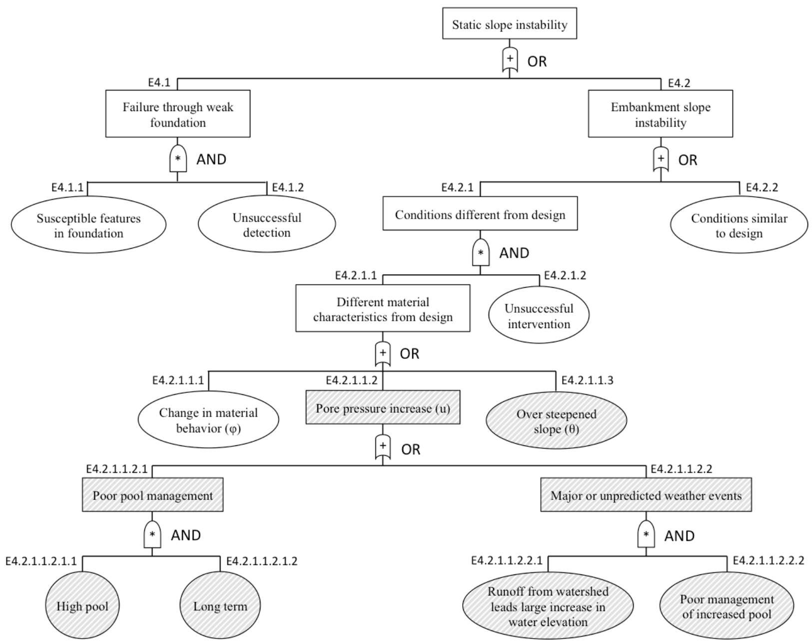


Fig. 40　Fault tree for static slope instability

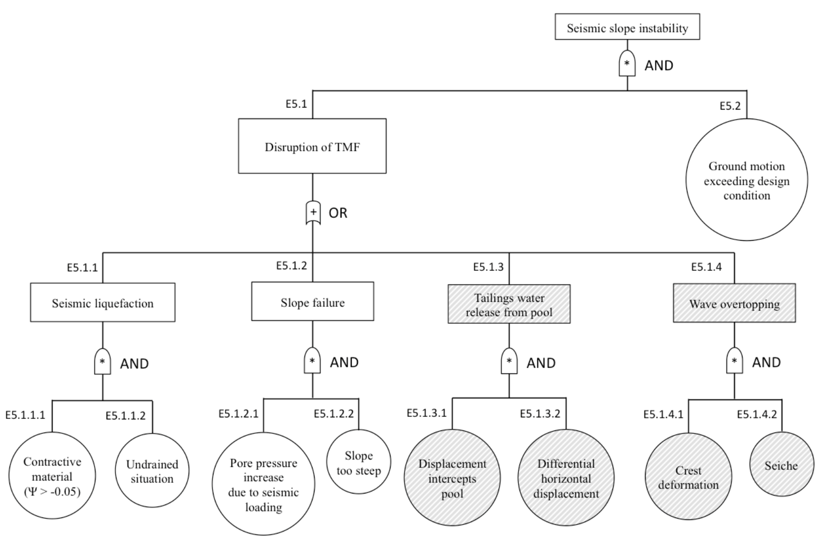


Fig. 41　Fault tree for seismic slope instability

Table 3 Probabilities of basic failure events

Event ID	Description	Remarks	Probability
Overtopping			
E1.1.1.1.1.1	Head cut advances to upstream face	Unsuccessful intervention or detection of head cut formation. Assume likelihood is 1:100.	0.0100
E1.1.1.1.1.2	Head cut formation	Tailings are highly erodible and likelihood of this event is estimated as 1:50.	0.0200
E1.1.1.1.2	Crest deformation	Has occurred at mines or dams. Assume likelihood is 1:400.	0.0025
E1.1.1.2	High pool	Assume management control in place. Likelihood of this event is 1:200.	0.0050
E1.1.2.1.1	Slurry inflow exceeds design capacity	Dependent on quality of tailings management. Assume it is well done and therefore the likelihood of this event is 1:200.	0.0050
E1.1.2.1.2	Natural ore variability	Dependent on experience in similar materials as well as using advanced prediction techniques. Assume likelihood is 1:200.	0.0050
E1.1.2.1.3	Design error	Extensive experience in slurry tailings is available. Assume likelihood is 1:200.	0.0050
E1.1.2.1.4	Exceedance of design criteria	Conditions based on design criteria are not achieved because of operational error or lack of climate change considerations. Assume likelihood is 1:100.	0.0100
E1.1.2.2.1	Heavy rain exceeds PMP	Similar to the previous event because climate change evaluations have not been included. Assume likelihood is 1:100.	0.0100
E1.1.2.2.2	Rapid thaw	Potentially resulting from climate change or incomplete climatic information. Assume likelihood is 1:100.	0.0100
E1.1.2.3	Unsuccessful intervention	Water surface elevation is kept at high for long term with unsuccessful or no intervention. Assume likelihood is 1:200.	0.0050

Event ID	Description	Remarks	Probability
E1.2.1	High pool	Similar to E1.1.1.2. Assume likelihood is 1:200.	0.0050
E1.2.2.1	Strong wind	Incomplete climatic information. Assume likelihood is 1:100.	0.0100
E1.2.2.2	Earth/Rock slide	Resulting from surrounding terrain slopes sliding into tailings basin. Assume likelihood is 1:100.	0.0100
Static liquefaction			
E2.1.1	Downstream surface eroded from overtopping	The likelihood was derived from calculations of the fault tree in Fig. 38.	0.0006
E2.1.2	Rapid embankment raise	Due to poor understanding of excess pore water pressure resulting from rapid raises. Assume likelihood is 1:100.	0.0100
E2.1.3.1.1	Slurry inflow exceeds expected amount	Similar to E1.1.2.1.1. Assume likelihood is 1:200.	0.0050
E2.1.3.1.2	Natural ore variability	Similar to E1.1.2.1.2. Assume likelihood is 1:200.	0.0050
E2.1.3.1.3	Design error	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E2.1.3.1.4	Exceedance of design criteria	Similar to E1.1.2.1.4. Assume likelihood is 1:100.	0.0100
E2.1.3.2.1	Different depositional behavior	Lack of understanding of tailings behavior, related to experience of designer. Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E2.1.3.2.2	Design error	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E2.1.3.2.3	Change in material characteristics	Has occurred due to ore body and processing changes. Assume likelihood is 1:100.	0.0100
E2.1.3.3.1	Heavy rain exceeds PMP	Similar to E1.1.2.2.1. Assume likelihood is 1:100.	0.0100
E2.1.3.3.2	Rapid thaw	Similar to E1.1.2.2.2. Assume likelihood is 1:100.	0.0100

Event ID	Description	Remarks	Probability
E2.2.1	Undrained situation	More likely in finer materials deposited near discharge points. Assume likelihood is 1:20.	0.0500
E2.2.2	Contractive material (Ψ > -0.05)	Most likely in weather climates where desiccation does not occur. Assume likelihood is 1:20.	0.0500
Downstream surface eroded from overtopping			
E2.1.1.1.1.1	Crest deformation	Similar to E1.1.1.1.2. Assume likelihood is 1:400.	0.0025
E2.1.1.1.1.2	High pool	Similar to E1.1.1.2. Assume likelihood is 1:200.	0.0050
E2.1.1.1.2.1.1	Slurry inflow exceeds design capacity	Similar to E1.1.2.1.1. Assume likelihood is 1:200.	0.0050
E2.1.1.1.2.1.2	Natural ore variability	Similar to E1.1.2.1.2. Assume likelihood is 1:200.	0.0050
E2.1.1.1.2.1.3	Design error	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E2.1.1.1.2.1.4	Exceedance of design criteria	Similar to E1.1.2.1.4. Assume likelihood is 1:100.	0.0100
E2.1.1.1.2.2.1	Heavy rain exceeds PMP	Similar to E1.1.2.2.1. Assume likelihood is 1:100.	0.0100
E2.1.1.1.2.2.2	Rapid thaw	Similar to E1.1.2.2.2. Assume likelihood is 1:100.	0.0100
E2.1.1.2.1	High pool	Similar to E1.1.1.2. Assume likelihood is 1:200.	0.0050
E2.1.1.2.2.1	Strong wind	Similar to E1.2.2.1. Assume likelihood is 1:100.	0.0100
E2.1.1.2.2.2	Earth/Rock slide	Similar to E1.2.2.2. Assume likelihood is 1:100.	0.0100
Internal erosion			
E3.1.1	Concentrated flow exists	Alluvial foundation subjected to continuous recharge from pool or other sources, less likely when experienced designer is involved. Assume likelihood is 1:100.	0.0100

Event ID	Description	Remarks	Probability
E3.1.2	Unsuccessful intervention	Concentrated flow in foundation is undetected or not treated properly. Assume likelihood is 1:200.	0.0050
E3.2.1.1.1	High water pressure	High water pressure can be tolerated in this case. Assume likelihood is 1:200.	0.0050
E3.2.1.1.2	Specific material susceptibility	Of similar magnitude to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E3.2.1.2	Initiation at the contact of the embankment and foundation	Feature in foundation is not identified during construction. Assume likelihood is 1:100.	0.0100
E3.2.2	Progression	With an adequate filter design, progression is less likely. Assume likelihood is 1:200.	0.0050
E3.3.1.1.1	High water pressure	High water pressure cannot be tolerated in this case. Assume likelihood is 1:100.	0.0100
E3.3.1.1.2	Specific material susceptibility	Similar to E3.2.1.1.2. Assume likelihood is 1:200.	0.0050
E3.3.1.2	Initiation at the contact of the embankment and foundation	Similar to E3.2.1.2. Assume likelihood is 1:100.	0.0100
E3.3.1.3.1	High water pressure	High water pressure cannot be tolerated in this case. Assume likelihood is 1:100.	0.0100
E3.3.1.3.2	Specific material susceptibility	Similar to E3.2.1.1.2. Assume likelihood is 1:200.	0.0050
E3.3.2	Progression	Without an adequate filter design, progression is more likely. Assume likelihood is 1:50.	0.0200
Static slope instability			
E4.1.1	Susceptible features in foundation	Cohesionless clay layers etc. exist in foundation. Assume likelihood is 1:100.	0.0100
E4.1.2	Unsuccessful detection	Similar to E3.1.2. Assume likelihood is 1:200.	0.0050
E4.2.1.1.1	Change in material behavior (ϕ)	Has occurred due to ore body or processing changes. Assume likelihood is 1:500.	0.0020

Event ID	Description	Remarks	Probability
E4.2.1.1.3	Over steepened slope (θ)	Resulting from undetected construction errors. Assume likelihood is 1:500.	0.0020
E4.2.1.1.2.1.1	High pool	Similar to E1.1.1.2. Assume likelihood is 1:200.	0.0050
E4.2.1.1.2.1.2	Long term	Assume management control in place. Likelihood of this event is 1:200.	0.0050
E4.2.1.1.2.2.1	Runoff from watershed leads large increase in water elevation	Similar to E1.1.2.2.1. Assume likelihood is 1:100.	0.0100
E4.2.1.1.2.2.2	Poor management of increased pool	Similar to E1.1.1.2. Assume likelihood is 1:200.	0.0050
E4.2.1.2	Unsuccessful intervention	Similar to E3.1.2. Assume likelihood is 1:200.	0.0050
E4.2.2	Conditions similar to design	Suppose TMF is constructed with good engineering practice and the factor of safety is 1.5. From the result of Silva et al. (2008), assume likelihood is 1:10000.	0.0001
Seismic slope instability			
E5.1.1.1	Contractive material (Ψ > -0.05)	Similar to E2.2.2. Assume likelihood is 1:20.	0.0500
E5.1.1.2	Undrained situation	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E5.1.2.1	Pore pressure increase due to seismic loading	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050
E5.1.2.2	Slope too steep	Similar to E4.2.1.1.3. Assume likelihood is 1:500.	0.0020
E5.1.3.1	Displacement intercepts pool	Displacement intercepts the impoundment inducing the release of tailings water. Likelihood of this event is 1:50.	0.0200
E5.1.3.2	Differential horizontal displacement	Has occurred at embankment due to seismic loading. Assume likelihood is 1:100.	0.0100
E5.1.4.1	Crest deformation	Similar to E1.1.1.1.2. Assume likelihood is 1:400.	0.0025

Event ID	Description	Remarks	Probability
E5.1.4.2	Seiche	Due to seismic loading, seiche occurs and generates high waves. Likelihood of this event is 1:200.	0.0050
E5.2	Ground motion exceeding design condition	Similar to E1.1.2.1.3. Assume likelihood is 1:200.	0.0050

In Table 3, if the basic probabilities are related to "OR" gates, then conditional probabilities are not considered. When they are related by "AND" gates then strictly speaking conditional probabilities (equation (5)) should be used. For most of these cases it is essentially done, e.g. for a sequence of events such as initiation event (intermediate event, E3.2.1) and progression event (basic event, E3.2.2) in the fault tree for internal erosion (Fig. 39). In this case, the probability of initiation (0.01) is multiplied by the probability of progression. The probability of progression is effectively a conditional probability (P[progression | initiation]) and the magnitude of this likelihood (0.005) reflects this conditionality.

Table 4 and Fig. 42 shows the likelihood of the individual failure modes as well as that for the combined failure that can result in tailings release to the environment. The likelihoods are listed for conventional tailings slurry and for dewatered tailings. Dewatered tailings have lower likelihoods of failure than conventional slurry tailings.

Table 4 Likelihood of failure and failure modes for slurry and dewatered TMF

Failure mode	Slurry	Dewatered
Overtopping	1.2×10^{-4}	0
Static liquefaction	1.9×10^{-4}	1.3×10^{-4}
Internal erosion	3.0×10^{-4}	0
Static slope instability	1.7×10^{-4}	1.6×10^{-4}
Seismic slope instability	2.4×10^{-6}	1.3×10^{-6}
Release of tailings to the environment	$\mathbf{7.8\times10^{-4}}$	$\mathbf{2.9\times10^{-4}}$

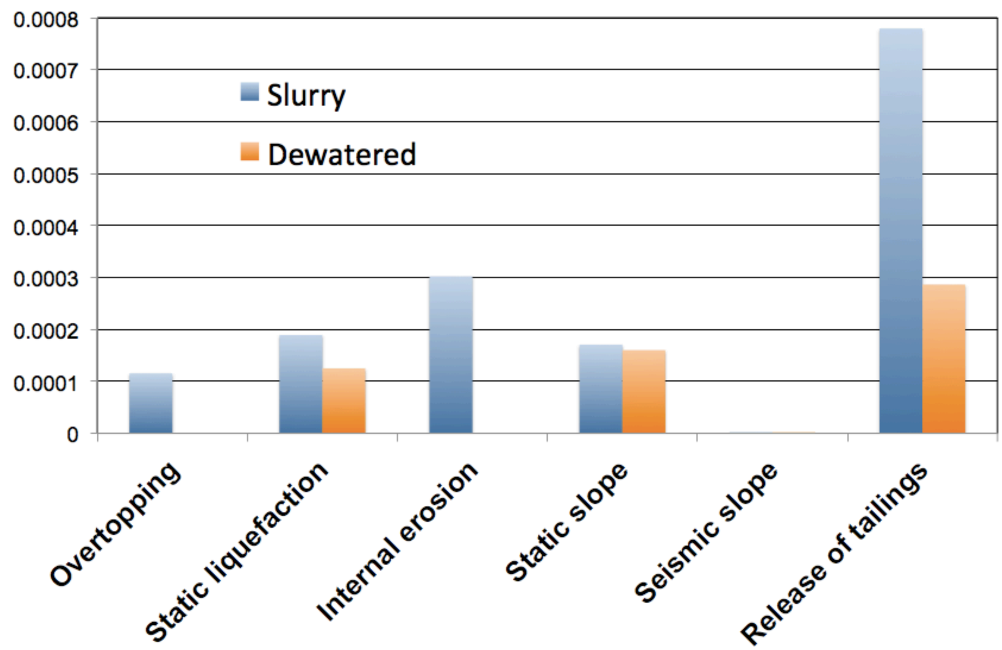


Fig. 42 Likelihood of failure and each failure mode for slurry and dewatered TMF

The failure likelihoods in Table 4 resulted from the structure of the fault trees and the qualitatively assigned likelihoods for basic events. Fig. 43 shows that the likelihood of the top event (release of tailings to the environment) is the same order of magnitude as the statistical values presented by Oboni and Oboni (2013).

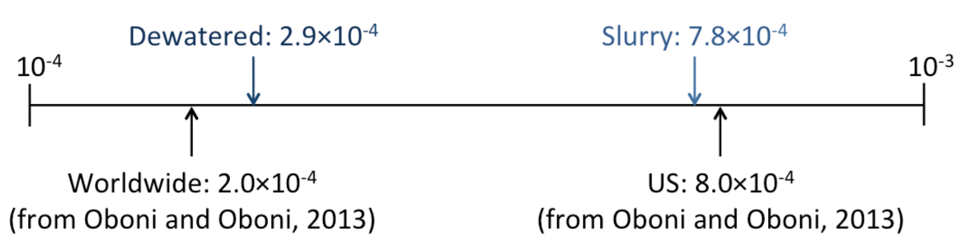


Fig. 43 Comparison of the results with historical values from Oboni and Oboni (2013)

The likelihood of slope failure (static slope instability and seismic slope instability) is encompassed in the range of values indicated by Silva, Lambe and Marr (2008). The important consideration is though that the likelihood of a tailings release from dewatered facilities is about 65% less than that for slurry tailings, even this seems like an under-estimate of the "improvements" resulting from dewatering.

5. Discussion

5.1 Overtopping

As contrasted with slurry tailings, the likelihood of overtopping for dewatered tailings is zero based on the fault tree shown in Fig. 36. Since there is no pond in well produced paste and filtered tailings management facilities, the likelihood of overtopping is obviously zero. Although a thickened tailings management facility could have an associated pond, in most cases it is separated from a tailings containment area. Therefore, the likelihood of overtopping in an associated pond causing the release of tailings to the environment is zero.

Another possible factor that can increase the likelihood of overtopping for thickened tailings is the toe containment berm. Thickened tailings itself or bleed water from deposited thickened tailings can overtop the toe containment berm. Even if this failure mode is considered, a thickened TMF is still expected to have a lower likelihood of tailings release if overtopping occurs than for conventional slurry tailings.

5.2 Static Liquefaction

The likelihood of static liquefaction for dewatered tailings is lower than for slurry tailings. This is reasonable because dewatered tailings have less water that plays a key role in strain softening response. More specifically, high phreatic surface because of poor pool management is not the event that will occur for dewatered TMFs because of the absence of a pond as stated above. The event, downstream surface eroded from overtopping, does not occur for dewatered TMFs as well for the same reason.

The likelihood of static liquefaction for dewatered tailings can be lower than estimated because the likelihood of some basic events would be lower than for slurry tailings. For instance, contractive material ($\Psi > -0.05$) is less likely to remain in dewatered TMFs, although it requires mechanical compaction and evaporative drying and desiccation for thickened and paste tailings to achieve negative state parameter ($\Psi < 0$) (Davies et al., 2002). For filtered tailings, static liquefaction is virtually impossible as long as it can be compacted well.

5.3 Internal Erosion

In order for internal erosion to occur, a continuous source for water flow through the embankment or foundation is required. In dewatered TMFs, it is highly unlikely that there is continuous water flow through embankment or foundation. Thus, there is a likelihood of internal erosion for slurry tailings but not for dewatered tailings.

The likelihood of internal erosion will be higher especially when there are continuous fine layers that may result in concentrated flows. Concentrated water flow would likely form between high permeability layer and low permeability layer of tailings and internal erosion may initiate. Hence the likelihood of internal erosion is highly dependent on site-specific conditions.

5.4 Static Slope Instability

The likelihood of static slope instability is slightly different between slurry tailings and dewatered tailings. Tailings containment areas and water catchment ponds are separated in different locations in dewatered TMFs. Hence, pore pressure increase in the embankment because of a large amount of water in the pool is not an event that will occur for dewatered tailings.

The likelihood of static slope instability for dewatered tailings can be much lower than estimated. As can be seen in Fig. 3, dewatered tailings have higher shear strength and less water content, which makes them more resistant to static slope instability.

5.5 Seismic Slope Instability

As with the other failure modes, seismic slope instability like the other events related to an impoundment, such as wave overtopping or tailings water release from pool, is less likely to happen for dewatered TMFs. The likelihood of contractive material is lower for dewatered tailings because dewatering and increased densification of tailings is more readily available than for slurry tailings. The likelihood of pore pressure increase due to seismic loading will also be lower than for slurry tailings since dewatered TMFs will tend to be more desaturated than slurry impoundments.

5.6 Application of Fault Trees to Site-specific Conditions

The framework developed above will be used to evaluate the failure of a specific tailings impoundment. The Bafokeng TMF failure of 1974 is selected as the sample case as literature and personal experience with the evaluation of this failure is available (Caldwell, 2014). Site information and the evaluation results are presented below.

5.6.1 Overview of Bafokeng TMF failure

The Bafokeng mine is located near Rustenburg in South Africa where the weather is very hot and dry. The No. 1 TMF was raised through upstream construction with typical ring dyke impoundment as shown in Fig. 44. Tailings are mostly sandy silt discharged from the perimeters (Fig. 45), clayey silt materials can occur in layers due to the depositional behavior on the beach or in the pool area.

Fig. 44 Ring dyke impoundment of Bafokeng Dam (after Caldwell, 2011)

Fig. 45 Perimeter slimes discharge of Bafokeng Dam (after Caldwell, 2011)

According to Blight et al. (1981), on November 11th 1974, the wall of the No. 1 TMF failed. Before the failure, the TMF contained about 1.3×10^7 m^3 of tailings. About 3×10^6 m^3 of tailings flowed through the breach in the wall, engulfed a vertical shaft of the mine killing 13 miners, and flooded down the valley of the Kwa-Leragane River, causing large scale environmental impacts. Fig. 46 shows the layout of Bafokeng No. 1. TMF and flooded area. Fig. 47 is a typical soil profile for the Rustenburg area.

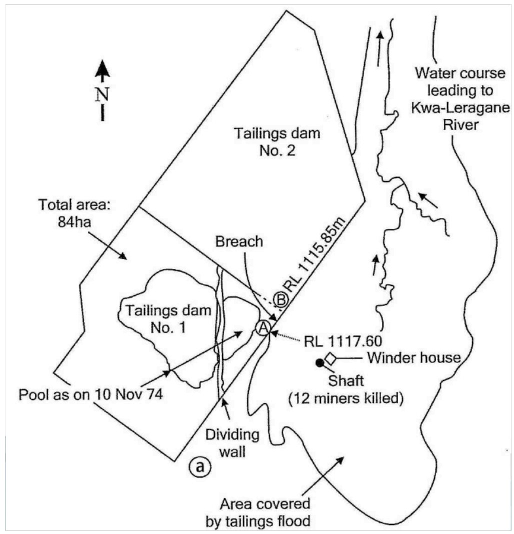


Fig. 46 Geography around Bafokeng No. 1 TMF at the time of failure (after Caldwell, 2011)

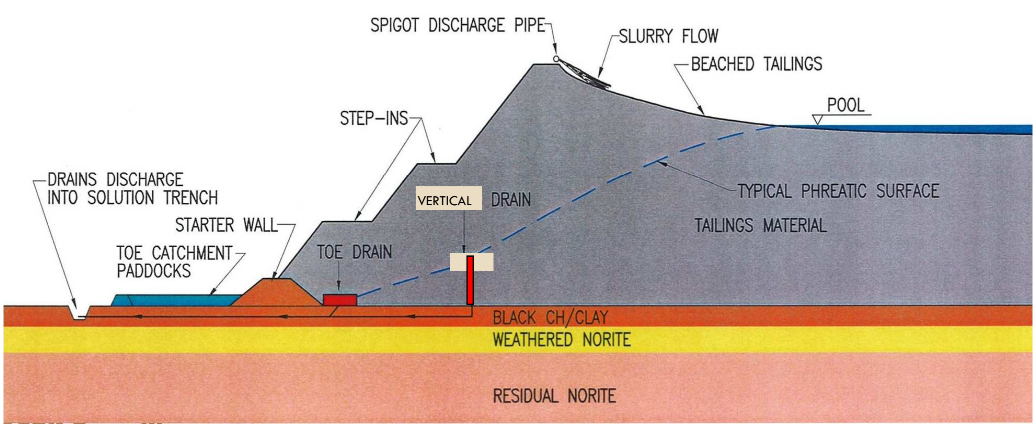


Fig. 47 Typical foundation conditions for a TMF in the Rustenburg area (after Caldwell, 2011)

5.6.2 Possible failure causes

The detailed description at the time of failure is provided by Caldwell and Charlebois (2010) as below:

"The mine, like all mines in the area, was perpetually short of water, so they stored as much water as possible on the top of the impoundment. The day of the failure, the pool was very close to and some say lapping up against the outer dike thrown up to make a place for the discharge pipes and the next lift of tailings discharge. Then it rained. The bulldozer driver was sent to shore up a vulnerable-looking part of the outer dike. Who knows: maybe he vibrated the wet tailings and they liquefied; maybe he dug too deep or too inexpertly with his bucket as he struggled in the rain to do something unfamiliar and he just took away the freeboard; maybe some profound geotechnical occurrence happened deep in the tailings. Regardless, the water and liquid tailings flowed out, flowed far, and killed miners." (Caldwell and Charlebois, 2010)

Caldwell and Charlebois (2010) also introduce the opinion of Prof. Jennings for whom Caldwell worked to collect the data to evaluate the failure. Prof. Jennings was convinced that piping from the nearby pool to the wall initiated between two layers of low permeability slimes bordering a zone of higher permeability sand tailings.

Blight who wrote about this failure in his book concludes that "It appears at first sight that the dyke did not fail by conventional overtopping. Eyewitness accounts all point to a failure by piping erosion. However, a satisfactory explanation of how the initial hole formed in the wall was never reached". (Blight, 2010)

With knowledge of those experts opinions, Caldwell and Charlebois (2010) reach their own conclusion that "the pool was too close to the perimeter dikes, it was raining hard, there was seepage flow in saturated sand layers between clay layers, and the bulldozer operator induced liquefaction in the confined sand layer." (Caldwell and Charlebois, 2010)

Summarizing the above, there are mainly 6 possible failure causes:

1. High pool because of poor pool management allowing the impoundment to rise close to the crest of the embankment leading to overtopping.
2. Emergency construction activities on the embankment dyke that causes conditions different from design that could have resulted to static slope instability or contractive walls leading to static liquefaction.
3. Weak clay foundation susceptible to slope slide leading to static slope instability.
4. Cyclic loads from a bulldozer on confined and saturated sand layers leading to static liquefaction or crest deformation leading to overtopping.
5. Loss of freeboard by operational error leading to overtopping.
6. Layering of low permeability slimes and high permeability sand tailings make a piping-susceptible condition leading to internal erosion.

Bafokeng Dam failure could be triggered by any of the above causes individually or any combinations of them.

5.6.3 Fault trees for Bafokeng TMF failure

Fig. 48 to Fig. 51 are the fault trees for these failure modes. These fault trees are structured only from the components of the generic fault trees presented above. The likelihoods of basic failure event listed in Table 3 are used where appropriate otherwise they are adjusted (qualitatively) to address the site conditions on the day of the failure. Table 5 lists the basic events and likelihoods that were used in calculating the probabilities of overtopping, static liquefaction and internal erosion. Table 6 shows the numerical result of fault tree analysis.

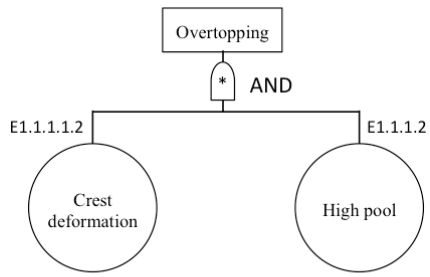


Fig. 48 Fault tree for overtopping at Bafokeng TMF

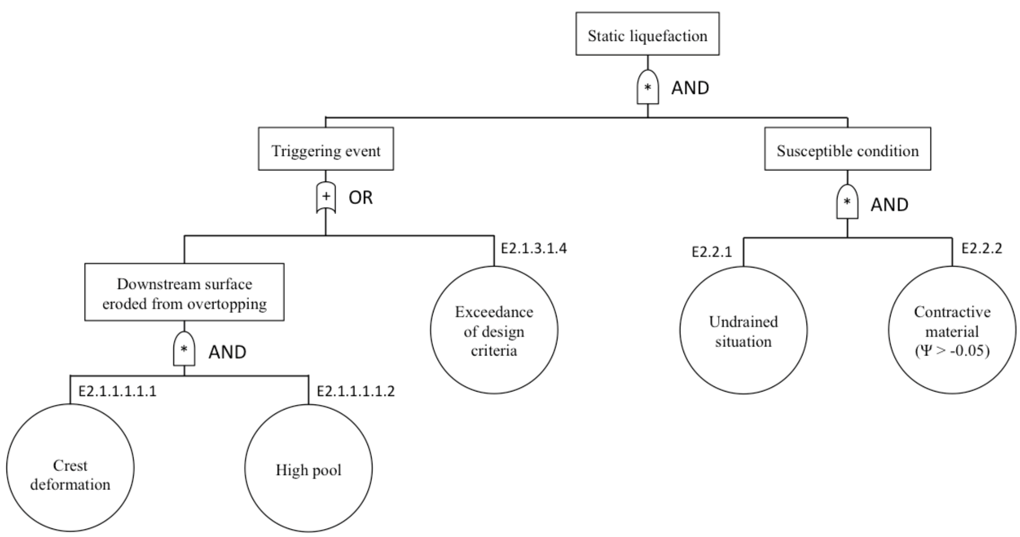


Fig. 49 Fault tree for static liquefaction at Bafokeng TMF

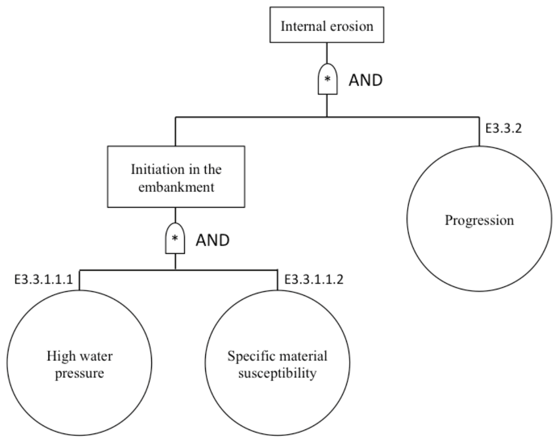


Fig. 50 Fault tree for internal erosion at Bafokeng TMF

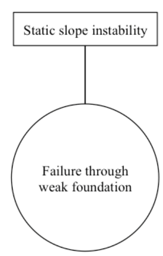


Fig. 51 Fault tree for static slope instability at Bafokeng TMF

Table 5 Likelihoods of basic failure events for Bafokeng TMF failure

Event ID	Description	Remarks	Likelihood
E1.1.1.1.2	Crest deformation	Bulldozer present on the embankment to shore up the vulnerable part	0.1
E1.1.1.2	High pool	Water stored as much as possible in the TMF because of water shortage in this region	0.5
E2.1.1.1.1.1	Crest deformation	Same as E1.1.1.1.2.	0.1

Event ID	Description	Remarks	Likelihood
E2.1.1.1.1.2	High pool	Same as E1.1.1.2.	0.5
E2.1.3.1.4	Exceedance of design criteria	More water kept in the TMF than design capacity to resolve water shortage	0.1
E2.2.1	Undrained situation	No toe drain installed into the TMF	0.1
E2.2.2	Contractive material ($\Psi > -0.05$)	Emergency construction of the dyke possibly without enough compaction observed	0.1
E3.3.1.1.1	High water pressure	Hard rain and high pool present at the day of the failure	0.05
E3.3.1.1.2	Specific material susceptibility	Permeable sand layers present between less permeable clay layers in the embankment	0.1
E3.3.2	Progression	Without an adequate filter design, progression is more likely	0.02

Table 6 Likelihood of failure modes for Bafokeng TMF failure

Failure mode	Likelihood of failure
Release of tailings to the environment	0.6721
Overtopping	0.0500
Static liquefaction	0.0015
Internal erosion	0.0001
Static slope instability	0.6200

To evaluate the static slope instability, reliability modeling of a foundation failure through the weak clay is analyzed since this is highly site-specific matter.

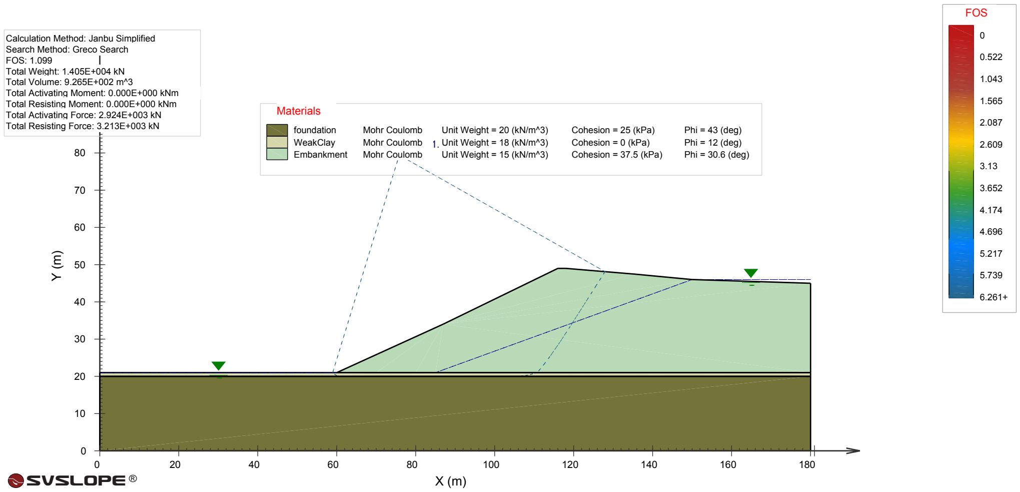


Fig. 52 Schematic static instability model for Bafokeng TMF

A probabilistic slope stability analysis was performed using and cross section constructed based on information provided by Caldwell. The section is shown in Fig. 52. The statistics of the shear strength values are shown in Table 7. An adjusted phreatic surface was selected that resulted in a factor of safety against static stability failure of about 1.0 when the average shear strength values were applied.

Table 7 Statistics of shear strength values for stability analysis

Parameter	Average Value	Coefficient of Variation, %	Standard Deviation
$c_{tailings}$	25 kPa	50%	12.5 kPa
$\Phi_{tailings}$	34 degrees	10%	3.4 degrees
$\Phi_{clay\ layer}$	10 degrees	20%	2 degrees

The Point Estimate Method expanded by Harr (1986) was used in estimating the mean and standard deviation of the factor of safety for slope stability. The results of the stability analysis are shown in Table 8.

Table 8 Factor of safety for 8 point estimates

Combination	Factor of Safety
+++	1.206
++-	1.017
+--	0.943
---	0.748
--+	0.898
-++	0.908
+-+	1.099
-+-	0.848

Note that the "combination" in the table determines the values of the shear strength parameters used for the stability analysis; the values are in the order listed in Table 7. So that in the case of "++-" the values used are:

$c_{tailings}$: average plus standard deviation

$\Phi_{tailings}$: average plus standard deviation

$\Phi_{clay\ layer}$: average minus standard deviation

The mean value of factor of safety is obtained from:

$$E(F) = \sum_{i=1}^{8} P_i F_i \tag{10}$$

, where the P_i s are the weights. For this calculation the weights have a constant value of 1/8, which results in the mean value of factor of safety of 0.96.

The variance (second moment around the mean) is calculated as follows:

$$Var(F) = E(F^2) - [E(F)]^2 \tag{11}$$

which results in the standard deviation of the factor of safety of 0.14. Assuming that the factor of safety is normally distributed, the probability of factor of safety less than one (P [FS<1]) is 0.62. Admitting that the factor of safety does not physically mean anything when it is less than zero, the probability of the factor of safety less than zero is negligibly small in this case (8.3×10^{-13}).

It turns out that the likelihood of static slope instability is very high as a result of fault tree analysis. Although the static slope instability would be the main failure of Bafokeng TMF, it seems to be reasonable to think that not only one failure but also a string of failures triggering each other causes this disastrous failure.

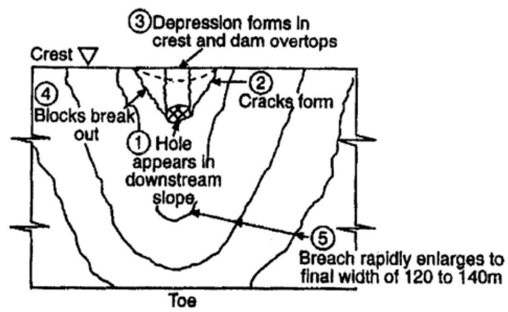


Fig. 53 A sequence of failure of Bafokeng TMF (after Blight and Fourie, 2003)

Fig. 53 presents the possible sequence of Bafokeng TMF failure. No matter how low the likelihood of each failure mode is, possibly all failure modes occur once one of them occurs.

5.7 Additional Slurry Tailings Failure Modes

Other than the failure modes described so far in this study, there are also some other possible failure modes for slurry tailings. One such failure is that of a penstock used for decanting supernatant. Fig. 54 shows the fault tree of penstock failure and it can lead to the release of tailings to the environment. However, it is not included in the fault tree for tailings release above as this form of supernatant removal is not universal for all slurry tailings TMFs. While it is still widely used in some geographic areas such as South Africa it is not a leading practice technology.

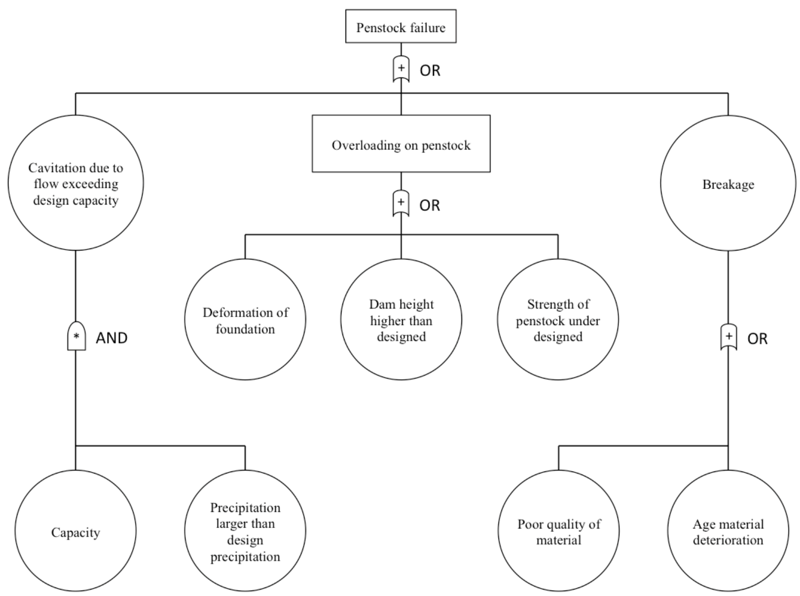


Fig. 54 Fault tree for penstock failure

For site-specific analysis, additional failures not covered in this study such as cracking or failures as a result of a string of incidents that are referred to Black Swan incidents in Caldwell and Charlebois (2010) should be considered.

5.8 Sources of Bias in This Thesis

There are two main sources of bias in this research. The first one is the structure of fault trees. Although the selection of failure modes is approached logically, it is based on by the author and had not been widely reviewed by industry professionals, it can therefore be biased. The other and the most significant source of bias is the use of subjective probabilities for the basic events. As stated in section 2.6, there are many steps in the estimation of subjective probabilities where biases can result in countless ways. By having more experts in the panel and asking them to provide a range of probabilities, it could be avoided or at least reduced.

6. Conclusion, Contributions and Recommendations for Future Research

6.1 Conclusion

This thesis has successfully addressed the objective that is to develop a framework for the estimation of the likelihood of failure for different tailings depositional alternatives: slurry, thickened, paste and filtered tailings.

The framework was developed to deal with the following issues: selection of representative failure modes for the depositional alternatives, development of the evaluation method and methodology to calculate the probability of failure.

Five failure modes (overtopping, static liquefaction, internal erosion, static slope instability and seismic slope instability) are selected based on the database established by ICOLD and UNEP (2001) to cover the majority of TMF failures.

Fault tree analysis was used to calculate the probability of failure as well as to understand how failures can happen. The 'Top level' event was defined as the release of tailings to the environment and five failure modes stated above are investigated in fault trees.

A form of expert elicitation was used to assign the probabilities for basic events. The structure of fault trees was reviewed by an external advisor.

The probability of the release of tailings to the environment for dewatered tailings was about 65% less than for slurry tailings.

The application of the fault trees to the evaluation of actual mine site, Bafokeng TMF, was also attempted. As a result, these generic fault trees at least successfully captured possible failure causes. However, it requires a careful consideration in regards to the likelihood of basic events because it highly depends on site-specific conditions.

Fault trees successfully visualized how the likelihood of failure shifts with the change in water content among tailings depositional alternatives.

Future-research expected to improve accuracy of fault tree analysis is presented in next chapter.

6.2 Contributions

The three major contributions from this research are that:

1. the development of a framework that can be used for the estimation of the likelihood of failure for various types of TMFs,
2. the fault tree diagrams that can be used to visualize the difference of failure likelihood between slurry and dewatered TMFs, and
3. the fault tree analysis that quantified the likelihood of failure for slurry and dewatered TMFs.

The framework developed in this research is useful in terms of flexibility. It can be used for the estimation of the likelihood of failure with the generic site assumptions as well as site-specific conditions if reliability modeling and adjustment of subjective probabilities are available.

The fault tree analysis quantified the likelihood of failure for slurry and dewatered TMFs. The estimation of failure likelihood for dewatered TMF has not been quantitatively analyzed yet in this field. Thus the results of this research would be beneficial for that purpose.

The result of fault tree analysis is quite unique in the way that it visualizes the differences of failure mechanisms and likelihoods between slurry and dewatered TMFs. It allows for a more intuitive understanding of the reliability difference between slurry and dewatered TMFs.

6.3 Recommendations for Future Research

- Apply framework to a number of site specific dewatered TMFs to further refine the failure causes and mechanisms
- Apply framework to downstream and centerline TMFs to further refine the failure causes and mechanisms
- Apply more complete expert elicitation of the fault trees and likelihoods of basic events
- Apply more reliability modeling approach to some basic events for further evaluation of the likelihood
- Consider development of fault trees that consider other top events, e.g. environmental impacts, operational failures, etc.

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