The British Dam Society

Risk-based approach for safety review of tailings dams

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SYNOPSIS The aim of this paper is to show, by way of a case study, how the risk-based approach to the safety review of dams can help dam owners prioritise upgrade options.

Risk-based assessment is a powerful tool to assess the safety of a dam by focusing on credible failure scenarios which will help identify risks, prioritise the required actions and eventually mitigate the risks in an efficient and cost-effective way. The main advantage of this method compared to the traditional standards-based assessment is the prioritisation of the risk mitigation options based on the risks associated with different failure modes.

This paper is based on a risk-based safety assessment that was carried out for an existing tailings dam, referred to herein as a Tailings Storage Facility (TSF). The objective of the study was to ensure that the risks to society are tolerable and to suggest several practicable risk mitigation options. As a result, the estimated risks for all loadings and failure modes were expressed as F-N plots representing the level of societal risk.

Although the risk profile of the TSF was determined to be in the risk-tolerable area, efficient risk mitigation options were evaluated which could reduce the risk significantly; however, due to the marginal initial risk of the project it was concluded that the project is satisfying ALARP at this stage of the construction.

INTRODUCTION

This paper evaluates the associated risk posed by a Tailing Storage Facility (TSF). SLR Consulting undertook the quantitative risk assessment and the required studies to evaluate the level of "life safety" risk and determine whether the facility meets the tolerable risk criteria outlined in the ANCOLD Guidelines on Risk Assessment (ANCOLD, 2022).

Standards-based assessments for this project were undertaken previously including geotechnical investigations and interpretation, stability assessments, numerical (finite element method) seepage and deformation analyses, monitoring and instrumentation, detailed design of the facilities, etc. The existing information above combined with Failure Modes and Effects Analysis (FMEA), Dam Break Assessment (DBA) and Consequence Category Assessment (CCA) of the facility was used for the purpose of the risk assessment associated with the failure of the main embankment.

The risk assessment process adopted is illustrated in Figure 1.

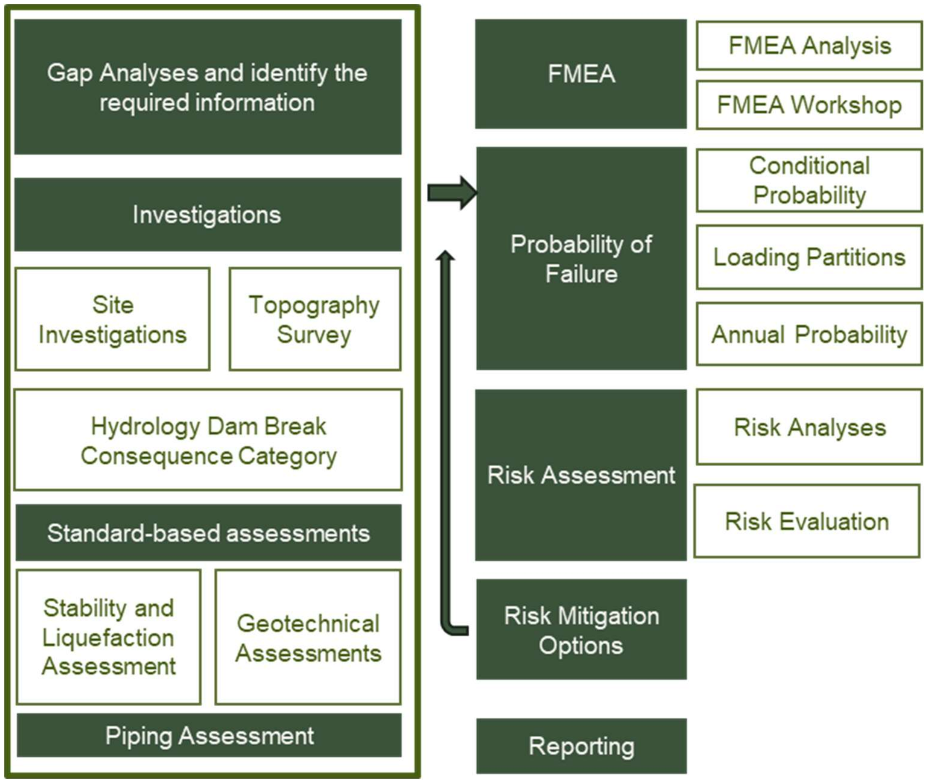


Figure 1. The process of the risk-based safety assessment

DAM BREAK AND CONSEQUENCE ASSESSMENT OUTCOME

Table 1 summarises the potential loss of life (PLL) estimated for each of the breach cases. Estimates of PLL have been developed by applying estimated fatality rates to the population at risk (PAR) for both a flood-induced dam break scenario and a no-dam break scenario for the same magnitude flood event. Incremental PLL is calculated as the increase in PLL between these two scenarios.

Table 1. Population at risk (PAR) and potential loss of life (PLL)

Scenario	Incremental PAR	Incremental PLL
Dam Break – Sunny day	6	6
Dam Break - 1:100 year	7	7
Dam Break - 1:1000 year	7	7
Dam Break - 1:10000 year	180	10

Note: The population at risk for the first three rows are mine workers who are working at the downstream toe of the embankment

Consequence Classification Assessment (CCA)

The facility has been assessed to be a High A consequence category facility, in accordance with the ANCOLD Guidelines on Tailings Dams (ANCOLD, 2019).

FAILURE MODES AND EFFECTS ANALYSES (FMEA)

A failure mode is defined as the way that a failure can occur, describing how an element or component failure must occur to cause loss of the sub-system or system function, and should form an essential part of a risk assessment.

During FMEA workshops, the following credible failure modes (FMs) were identified for further assessment as part of the quantitative risk assessment (QRA). (Table 2)

Table 2. Credible failure modes for the purpose of risk assessment

FM	Initiating	Failure Mode (FM)
ST1E	Earthquake	Instability of the embankment due to liquefaction of the tailings
ST2F	Normal/Flood	Downstream embankment slope instability due to flood loading
IM7F	Normal/Flood	Piping initiated by transverse cracking in the embankment crest due to desiccation by drying (IM7-Piping Toolbox)
IM14F	Normal/Flood	Piping initiated by continuous high permeability layer in the embankment (IM14-Piping Toolbox)
OVF	Normal/Flood	Failure due to scour erosion of the crest because of overtopping

ASSESSMENT OF THE CONDITIONAL PROBABILITIES OF FAILURE

The evaluation of the probabilities of failure was based on the event tree approach. An event tree consists of a series of linked nodes and branches. Each node represents an uncertain event or condition, while each branch represents one possible outcome of the event or one possible state that a condition may assume (i.e., the system response).

Potential of Failure Due to Instability of the Embankment

The stability evaluations were performed for the embankment for long-term, short-term and post-liquefied conditions.

SLOPE/W software (part of GeoStudio 21 R2) was used to evaluate embankment stability by applying the Morgenstern-Price method of slices to the section. The results are summarised in Table 3. The safety factors have been improving since 2022 due to the ongoing construction of a rockfill buttress at the embankment toe.

Table 3. Slope stability safety factors (FoS) obtained from the analyses

Analyses	FoS
Drained	2.5
Undrained	1.4
Post-Liquefied	1.0

Conditional Probability of Failure Due to Instability of the Embankment (ST2F)

Event tree probabilities for this failure mode due to non-seismic failure of the embankment are tabulated in Table 4 and the system response curve is presented in Figure 2.

Table 4. The conditional probability of failure due to instability of the embankment –ST2F

Flood levels (mAHD)	Probabilities				
	Slope instability (1)	Tailings overtopping(2)	Scour erosion(2)	Breach	Conditional Probability
809.00 (F1)	1.00E-04	1.00E-02	1.00E+00	1.00E-01	1.00E-07
810.00 (F2)	1.00E-04	1.00E-01	1.00E+00	1.00E-01	1.00E-06
810.41 (F3)	1.00E-04	1.00E-01	1.00E+00	5.00E-01	5.00E-06
810.94 (F4)	1.00E-04	1.00E+00	1.00E+00	1.00E+00	1.00E-04
811.40 (F5)	5.00E-03	1.00E+00	1.00E+00	1.00E+00	5.00E-03
>811.4 (F6)	1.00E-02	1.00E+00	1.00E+00	1.00E+00	1.00E-02

Notes:

1. These probabilities are based on the safety factors obtained from stability assessment and the system response curve based on reliability theory

2. These probabilities are based on the mapping scheme linking the description of likelihood to quantitative probability adopted by Barnie et al 1996

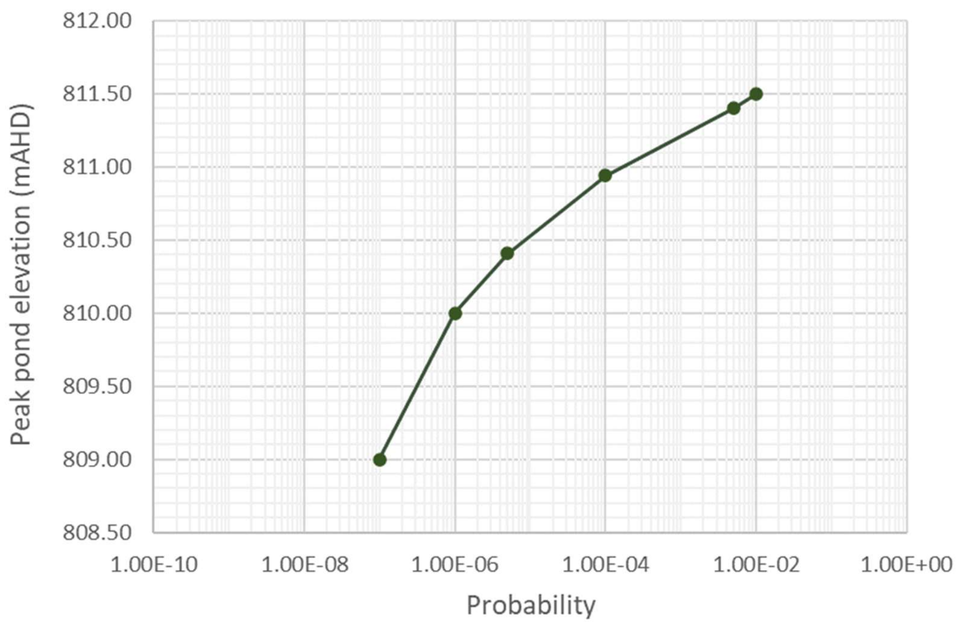


Figure 2. System response curve - failure due to instability of the embankment – ST2F

Conditional Probability of Failure Due to Instability of the Embankment (ST1E)

Event tree probabilities for this failure mode due to post-seismic liquefaction of the tailings material are tabulated in Table 5 and the event tree chart is presented in Figure 3. The resultant system response curve is shown in Figure 4.

Table 5. Conditional probability of failure due to instability of the embankment

Representative PGA for load partition (g)	Probabilities				
	Liquefaction of tailings(1)	Post seismic instability(2)	Tailings overtopping(3)	Uncontrolled release(3)	Conditional Probability
S1- 0.05	5.0E-04	4.0E-02	1.0E-03	1.0E+00	2.0E-08
S2- 0.08	4.0E-02	4.0E-02	1.0E-02	1.0E+00	1.6E-05
S3- 0.15	1.1E-01	4.0E-02	1.0E-01	1.0E+00	4.6E-04
S4- 0.23	8.5E-01	4.0E-02	5.0E-01	1.0E+00	1.7E-02
S5- 0.23<ag	9.9E-01	4.0E-02	1.0E+00	1.0E+00	4.0E-02

Notes:

1. These probabilities are based on the methodology recommended by Robertson (Robertson and Cabal, 2022)

2. These probabilities are based on the safety factors obtained from stability assessment and the system response curve based on reliability theory

3. These probabilities are based on the mapping scheme linking the description of likelihood to quantitative probability adopted by Barnie et al 1996

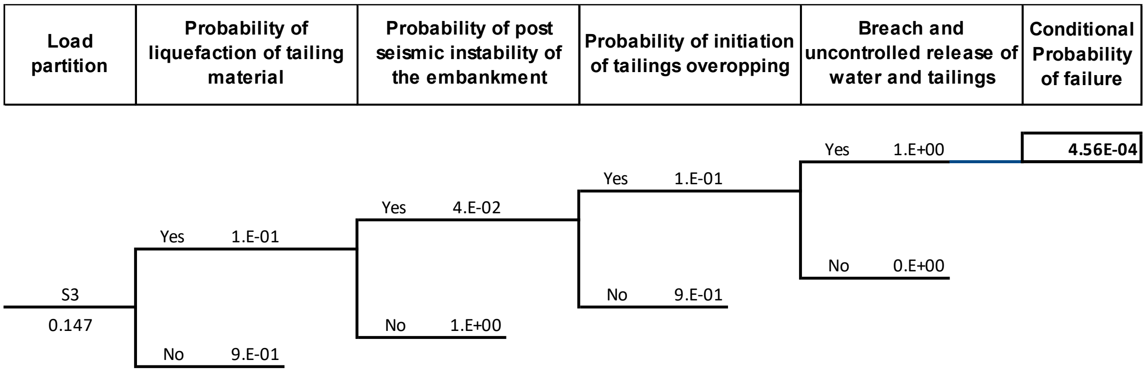


Figure 3. Event tree - failure due to instability of the embankment

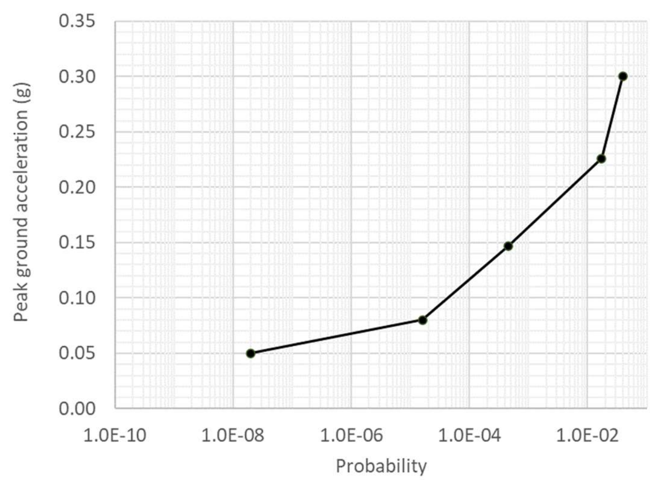


Figure 4. System response curve - failure due to instability of the embankment

Potential for Internal Erosion and Piping

Assessment of the potential for internal erosion and piping has followed the procedures of the Piping Toolbox[1] which is a systematic approach based on event tree analyses and includes the following five steps. A schematic showing different steps of the piping toolbox approach is demonstrated in Figure 6.

In order to apply the Piping Toolbox to a TSF the outer tailings zone is assumed to represent the core of the embankment dam and the upstream zone closer to the pond the upstream shoulder and the material properties for both the core and upstream shoulder are similar.

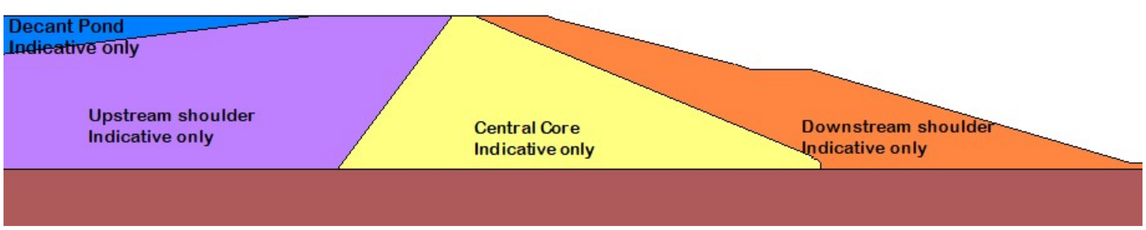


Figure 5. Schematic sketch of the zones for the purpose of piping assessment

[1] Piping Toolbox is a Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping Guidance Document developed by the University of NSW, URS, US Army Corps of Engineers, and US Bureau of Reclamation (Gilbert and UNSW, 2009).

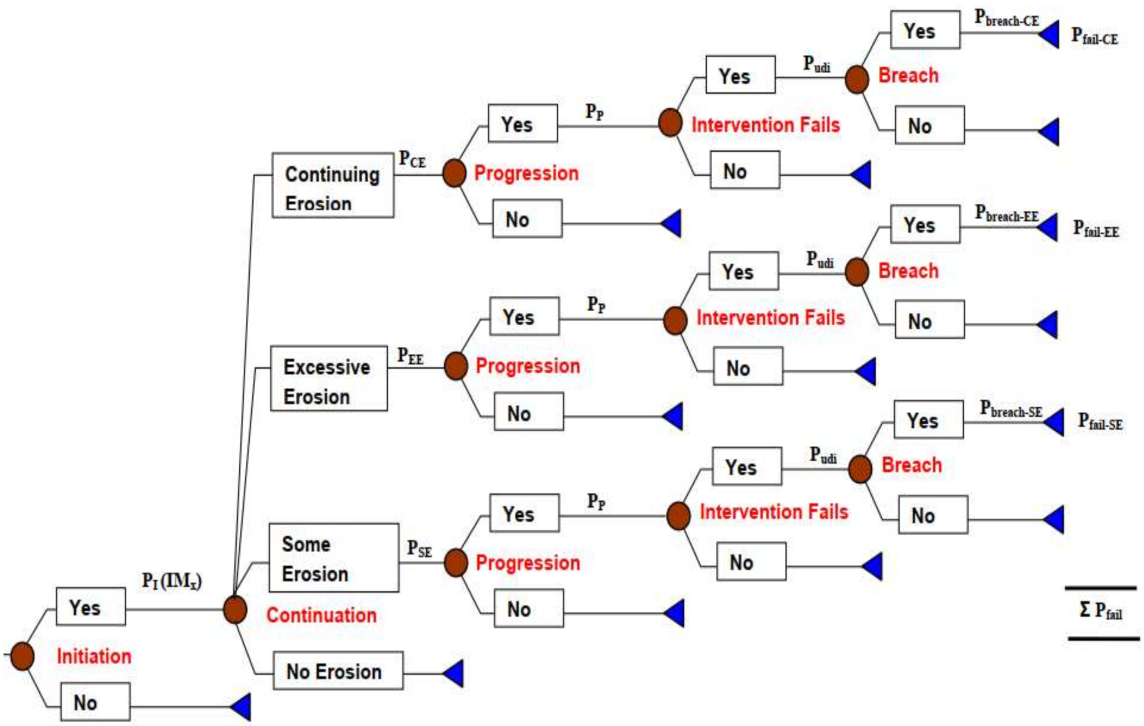


Figure 6. Event tree structure following piping toolbox 2008

Piping Failure because of Cracking in the Crest Due to Desiccation by Drying (IM7F)

Desiccation cracks are tensile cracks that occur because of the combination of drying and an increase in suction forces developed in the materials forming the crest. The system response curve associated with this FM is demonstrated in Figure 7.

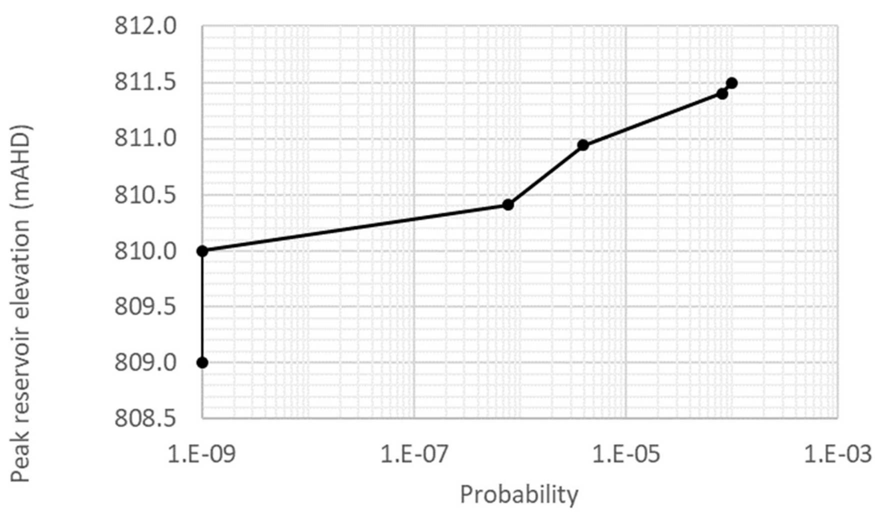


Figure 7. System response curve for piping failure (IM7F)

Piping Failure Because of High Permeability Zone in the Embankment (IM14F)

The crack initiation and propagation mechanism is dependent on soil compaction, mineralogy, initial moisture content, etc. Considering the tailings are hydraulically deposited and generally loose, it was assumed that all layers are poorly compacted. The system response curve associated with this FM is demonstrated in Figure 8.

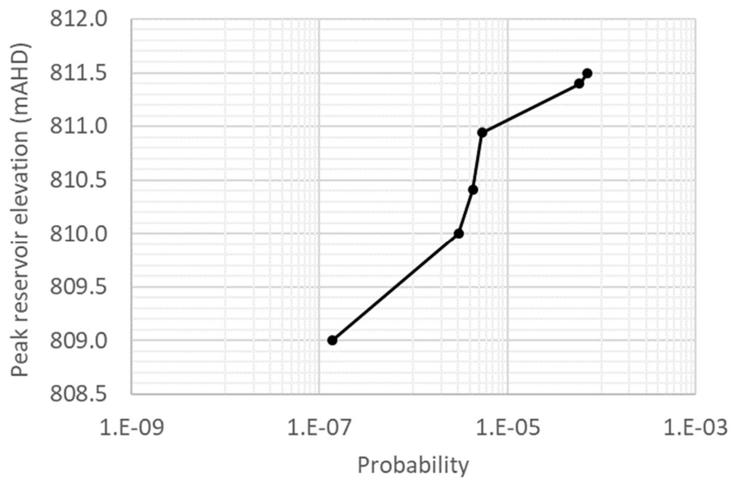


Figure 8. System response curve for piping failure (IM14F)

ASSESSMENT OF THE ANNUAL PROBABILITY OF FAILURE

This section includes estimating annual probabilities of various loading ranges (e.g. flood or earthquake) and estimating the annual probability of failure of the facility by combining the annual probabilities of the loading partitions with the conditional probabilities of the credible failure scenarios.

Load Partitioning

The resultant flood and seismic frequency curves for the TSF provide relevant frequency data for preparing a peak water level and peak ground acceleration (PGA) versus annual exceedance probability (AEP), which was used for the calculation of the annual probability of failure, risk assessment and risk evaluation.

Based on the frequency curves mentioned above, flood levels and PGAs were partitioned into a number of loading partitions as summarised in Table 6. Conditional probabilities of failure are estimated for each of the flood partitions (F1 to F6) and seismic partitions (S1 to S5), and for each credible failure mode identified from the FMEA.

Table 6. Flood loading partitions for annual probability assessment

Event	Group name	Event	Description	Representative Level (mAHD)/PGA(g)	Annual Probability of occurrence
Flood	F1	Flood	Mean decant pond level	809.0	5.50E-01
Flood	F2	Flood	1/100 Flood event	810.0	4.40E-01
Flood	F3	Flood	1/1000 Flood event	810.4	9.00E-03
Flood	F4	Flood	Spillway sill level	811.0	9.00E-04
Flood	F5	Flood	Crest at 111.4 mAHD	811.4	1.00E-04
Flood	F6	Flood	Above the crest	811.4<Flood level	5.00E-07
Seismic	S1	Seismic	Below 500 years event	0.05	9.98E-01
Seismic	S2	Seismic	500 years event	0.08	1.50E-03
Seismic	S3	Seismic	2000 years event	0.15	3.00E-04
Seismic	S4	Seismic	5000 years event	0.23	1.00E-04
Seismic	S5	Seismic	10000 years event	$0.23<a_g$	1.00E-04

Dam Failure Due to Slope Instability

The annual probabilities of breach due to these failure modes have been estimated by combining the conditional probabilities with the annual probabilities of the load partitions. (Table 7)

Table 7. Annual probability of failure due to slope instability

Load partitioning	Partition likelihood	Representative flood level (mAHD)	Annual Probability	Total Annual Probability
F1	5.50E-01	809.00	5.5E-08	1.13E-06
F2	4.40E-01	810.00	4.4E-07	
F3	9.00E-03	810.41	4.5E-08	
F4	9.00E-04	811.00	9.0E-08	
F5	1.00E-04	811.40	5.0E-07	
F6	5.00E-07	>811.4	5.0E-09	
S1 to S5	NA	809.00	5.85E-06	5.85E-06

Note: Seismic-related failure probabilities will be included in F1 load partitioning.

Probability of Failure Due to Piping

The annual probabilities of breach due to these failure modes have been estimated by combining the conditional probabilities mentioned above with the annual probabilities of the loading partitions and are presented in Table 8.

Table 8. Annual probability of failure due to piping (IM7F)

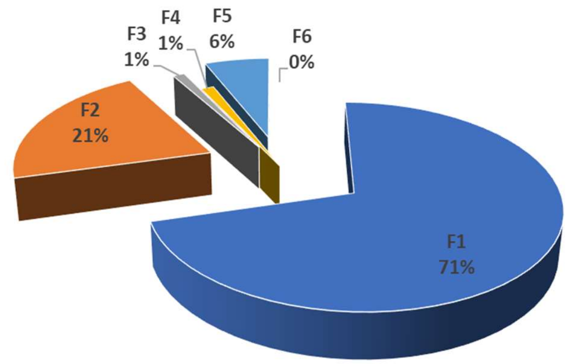
Loading partition	Representative level mAHD	Partition probability	Annual Failure probability (IM7F)	Annual Failure probability
F1	809.00	5.50E-01	5.50E-10	7.52E-08
F2	810.00	4.40E-01	4.40E-10	1.33E-06
F3	810.41	9.00E-03	6.87E-09	3.88E-08
F4	811.00	9.00E-04	3.55E-09	4.83E-09
F5	811.40	1.00E-04	8.01E-09	5.83E-09
F6	>811.4	5.00E-07	5.05E-11	3.57E-11
Total			**1.95E-08**	**1.46E-06**

Contribution of Each Loading Partition to the Annual Probability of Failure

Table 9 presents a summary of the estimated annual probabilities of failure of the TSF and contribution of each loading partition to the total failure.

Table 9. Estimated annual probabilities of failure for different loading partitions

Loading Partition	Annual Probability	Contribution (%)
F1	6.0E-06	70.69%
F2	1.8E-06	20.98%
F3	9.1E-08	1.07%
F4	9.8E-08	1.16%
F5	5.1E-07	6.04%
F6	5.1E-09	0.06%
	8.5E-06	**100.00%**

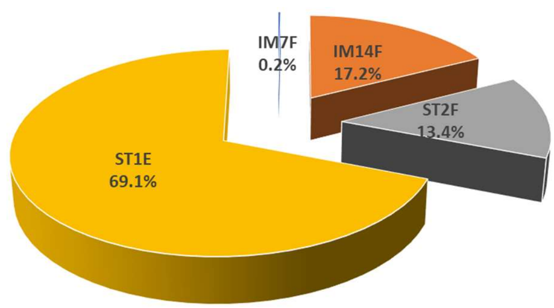


Contribution of Each Failure Mode to the Annual Probability of Failure

Table 10 presents a summary of the estimated annual probabilities of failure of the TSF due to the different failure modes that were assessed. From this table, failure due to slope instability contributes to around 82.5% of the total annual failure probability of $8.5x10^{-6}$ whereas failure due to piping contributes around 17.5%.

Table 10. Estimated annual probabilities of failure for each failure mode

FM Number.	Annual Probability	Contribution (%)
IM7F	1.9E-08	0.23%
IM14F	1.5E-06	17.24%
ST2F	1.1E-06	13.38%
ST1E	5.9E-06	69.14%
Total	**8.5E-06**	**100.00%**



RISK ASSESSMENT

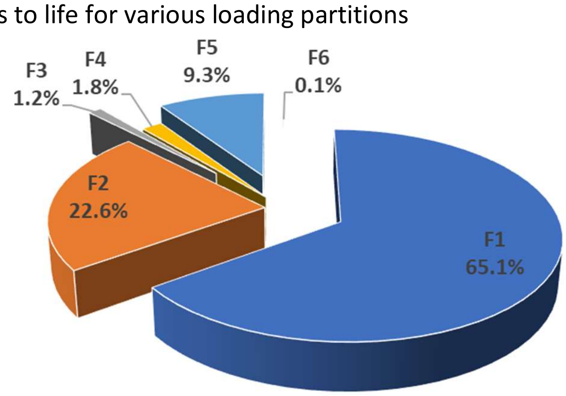
This section presents the result of the risk assessment of a failure through the TSF embankment and compares the estimated risks to the risk tolerability criteria for existing dams specified in the ANCOLD Guidelines on Risk Assessment (ANCOLD, 2022).

Estimation of Societal Risk

Table 11 summarises the estimated annual risks to life due to a failure of the TSF and the contribution of different loading partitions to the total risk.

Table 11. Annual risks to life for various loading partitions

Loading Partition	Risk	Contribution
F1	3.6E-05	65.14%
F2	1.2E-05	22.55%
F3	6.3E-07	1.15%
F4	9.8E-07	1.79%
F5	5.1E-06	9.28%
F6	5.1E-08	0.09%
Total	**5.5E-05**	**100.00%**

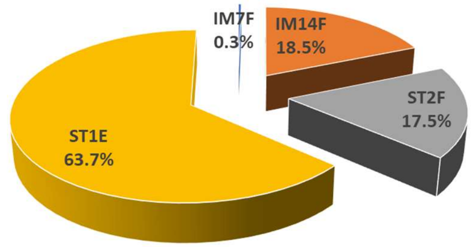


Estimation of Societal Risk

Table 12 summarises the estimated annual risks to life due to a failure of the TSF for the various failure modes assessed and their contributions to the total risk.

Table 12. Annual risks to life for various failure modes

Failure mode	Risk	Contribution
IM7F	1.7E-07	0.31%
IM14F	1.0E-05	18.46%
ST2F	9.7E-06	17.52%
ST1E	3.5E-05	63.71%
Total Risk	**5.5E-05**	**100.0%**



RISK EVALUATION

The plot position of the F-N curve presented as Figure 9 indicates the level of societal risk posed to the public. The diagonal line represents the safety threshold for societal risk associated with existing dams as recommended by ANCOLD (2022). The F-N plot shows that the level of societal risk posed by the TSF is below the specified safety threshold by around two orders of magnitude.

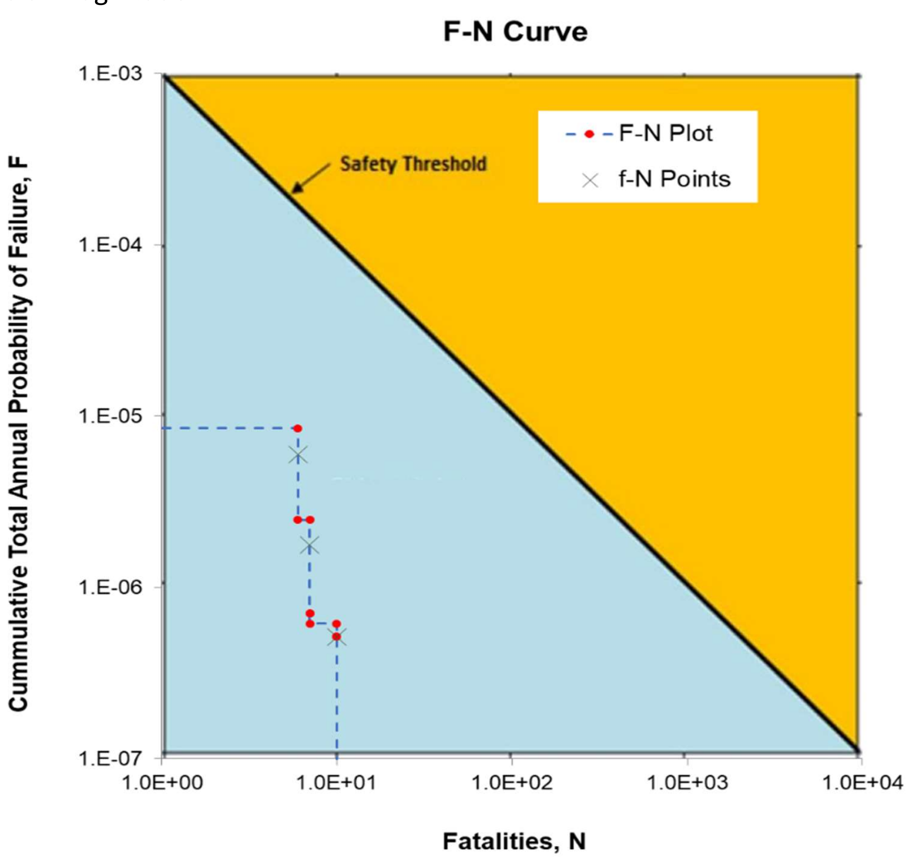


Figure 9. F-N plot showing the level of societal risk (Figure 7.4 ANCOLD 2022)

The estimated individual risk associated with TSF failure is 4.23×10^{-6} per annum, which is lower than the safety threshold of 10^{-4} per annum for an existing dam as recommended by ANCOLD (2022).

ALARP PRINCIPLES AND RISK MITIGATION OPTIONS

Both ANCOLD (2022) and the Global Industry Standard on Tailings Management (GISTM) (GTR, 2020) require risk reduction measures to be implemented to reduce risks for each credible failure mode to a level that the risk is as low as possible while the mitigation option is reasonably practicable, known as ALARP.

The most appropriate of the identified risk reduction measures would need to be further developed to determine basic definition and costing. The following options were initially considered:

1) Enhanced emergency evacuation procedures
2) Relocation of mining personnel most at risk
3) Installation of geotextile on the upstream embankment and adjacent tailings beach
4) Further buttressing of the downstream shoulder of the embankment

Among the items above, the first two items were considered to be administrative control and will mitigate the risk by managing the consequence, while the remaining two items will focus on reducing the probability of failure.

Residual Risk due to Enhanced emergency evacuation procedures, and the Relocation of mining personnel at risk in the immediate vicinity of the downstream toe

Considering the high fatality rate in the immediate vicinity of the TSF embankment, it was recommended to relocate mining personnel to another location with a lower risk. Assuming the total number of personnel in the area, including contractors and dam operators, can be reduced to 50% this will reduce the societal risk to 2.8×10^{-5}, which is 50% of the original risk. Considering that the initial risk is relatively low and although the risk reduction option would reduce the risk significantly, the cost of saving a statistical life (CSSL) is much more than the value of a statistical life (VSL) in Australia.

Residual Risk after Construction of Downstream Buttress

Construction of a downstream buttress is ongoing and it can be assumed at each stage it will improve the embankment stability safety factors by 10%. Based on this assumption, the residual risk is estimated to be 47% of the primary risk. Again, considering the initial risk is relatively low and although the risk reduction option would reduce the risk considerably, the CSSL is much more than the VSL in Australia.

Residual Risk after Applying a Geotextile Cover on the Upstream Embankment

The inclusion of embankment upstream geotextile protection was considered which may provide a risk reduction, add resiliency and/or improve facility operation. The residual risk is estimated to be 82% of the primary risk which is less effective than the other mitigation measures.

CONCLUSION

- Risk-based assessment of the safety status of dams and tailings facilities will enable us to understand the actual risks associated with different components of the project.
- Defining the risk profile of the project will help dam owners to proceed with the best upgrade option to mitigate the risk more efficiently.

Managing Risks for Dams and Reservoirs

- In certain instances, managing the dam failure consequences to reduce risk is more efficient, economical and quicker than reducing the probability of failure. This can be defined relatively simply by undertaking a risk-based safety review.
- When the initial risks are well below accepted safety thresholds (e.g. those provided by ANCOLD (2022)), the justification for risk reduction becomes more challenging. therefore, the justification to satisfy the ALARP principles will be more straightforward.

ACKNOWLEDGEMENTS

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