A quantitative risk assessment of seismic slope stability for a tailings dam

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ABSTRACT

Tailings are a by-product of mining, consisting of silts and sands from the processed rock or soils and susceptible to liquefaction under earthquakes. Tailings Storage Facilities (TSFs) include dams that are designed and managed to contain the tailings produced by a mine. Earthquake is one of the leading causes of incidents for tailings dams according to the review of historic dam data. This paper presents a quantitative risk assessment (QRA) on the potential failure modes of a tailings dam in closure due to seismic slope instability. The tailings dam in this case study is located in an area of moderately high historic seismicity. There are nearby active faults capable of M_w>6.0 earthquakes. The risk assessment has been undertaken to adhere to the Global Industry Standard on Tailings Management (GISTM) and state-of-practice guidelines, with the goal of zero harm to people and the environment with zero tolerance for human fatality. The assessment includes a robust evaluation of the potential failure mechanisms that could lead to a catastrophic failure of the dam, the estimation of failure consequences, an event tree analysis to quantify the failure probabilities and a comparison of the risk against recommended risk tolerability limits. The case study uses a potential failure mode associated with seismic slope instability as an example to demonstrate how the site-specific characteristics of tailings dam in terms of its design, construction, operation, and management, are considered and evaluated in the risk assessment, to inform the actions required to achieve the as low as reasonably practical (ALARP) principle. The techniques used in this assessment can be applied in other high-risk industries.

1 INTRODUCTION

Tailings are a by-product of mining, consisting of silts and sands from the processed rocks and interstitial water from processing. Tailings are susceptible to flow liquefaction due to its nature which is like a loosely deposited alluvium. Tailings dams are embankment structures designed and constructed to impound tailings. They also store water that is released when the tailings are deposited (supernatant water) and water from direct rainfall and runoff. The water is pumped to the process plant. The tailings dam may be used to store excess water as part of the project water management, and water is sometimes retained for environmental protection or geochemical stability reasons. Tailings dam are generally embankment dams constructed from compacted earthfill, rockfill, or as a combination of both sourced as overburden from open pits, underground mining or local borrow. In some cases, the coarse fraction of the tailings stream is used. The construction and operation of tailings dams can occur simultaneously over long periods of time with numerous stages of construction. The geometry may change as mining progresses, requiring design modifications with the advancement of construction. Furthermore, the properties of stored tailings may differ significantly at various stages of life cycle of a tailings dam. After deposition in the TSF, the physical properties of the tailings change with a reduction in water content due to consolidation and desiccation, or chemical effects in some circumstances.

Since tailings dams are complex systems, their reliability is contingent on appropriate execution in planning, investigation, analysis, construction quality, operational diligence, monitoring, regulatory action, and risk management at every level. The catastrophic failure of Feijão tailings dam in 2019 resulted in the loss of 270 lives and extensive damage of houses, farm, roads, and the natural environment downstream (Christian Plumb, 2020). The disaster triggered the development of the Global Industry Standard on Tailings Managements (GISTM, 2020). The goal of GISTM is to achieve zero harm to people and the environment with zero tolerance for human fatality. One of the requirements in GISTM is to "*address all potential failure modes of the structures, its foundation, abutments, reservoir (tailings deposit and pond), reservoir rim and appurtenant structures to minimise risk to As Low As Reasonably Practical (ALARP). Risk assessments must be used to inform the design*". Identification of potential failure modes (PFMs) and risk assessment should be repeated through the life of the facility, particularly if there is material change. For closure design, an appropriate design criterion to consider in the analysis of credible failure modes relative to non-credible failure modes may be on the order of 1 in 10,000 Annual Exceedance Probability (AEP).

Slope stability and earthquake are the two most frequent incident causes reported in the case history of tailings dam failures (ICOLD, 2001). This paper presents a quantitative risk assessment (QRA) on the potential failure modes of a tailings dam following closure due to seismic slope instability. The assessment was undertaken in accordance with the ANCOLD (Australian National Committee on Large Dams) Guidelines on Risk Assessment published in 2022 (ANCOLD, 2022) and GISTM. The process includes a robust evaluation of potential failure modes, assessment of consequences, estimation of failure probabilities, assessment of risk tolerability, and demonstration of meeting the ALARP principle. The outcome of QRA was used to inform engineering decision on the measures required for controlling potential failure modes. It is anticipated that the techniques learnt from this assessment can also be applied by the other high-risk industries.

2 PROJECT BACKGROUND

The project site is in a region of moderately high seismicity in New Zealand. Twelves active faults that can generate earthquake with $M_w > 6.0$ have been identified within 50 km of the project site. Two levels of design earthquakes are recommended to be considered according to New Zealand Dam Safety Guidelines (NZSOLD, 2015), i.e. Operating Basis Earthquake (OBE) and Safety Evaluation Earthquake (SEE). The return periods of design earthquake are selected based on the Potential Impact Classification (PIC) of the dam. The PIC for the TSF is High, and the OBE is ground motion with a 1 in 150 Annual Exceedance Probability (AEP) and the SEE is ground motion with a 1 in 10,000 AEP. Estimates of response spectra for the design earthquakes are based on the 2022 New Zealand National Seismic Hazard Model (NSHM) published by GNS (2022). The corresponding Peak Ground Acceleration (PGA) values are 0.2 g and 1.29 g, respectively. In the OBE, the tailings dam is required to remain operational, with any damage being minor and readily repairable. In the SEE, deformations are acceptable but there should be no uncontrolled release of the reservoir.

The tailings dam assessed in this case study is a zoned earthfill and rockfill embankment with a chimney drain. The construction materials were conditioned waste rock from the open pit mining. A typical cross-section of the dam is shown in Figure 1. The embankment was designed for a maximum height of 38 m, it was only necessary to build to 35 m to meet the final tailings production totals. The starter embankment had a core constructed with compacted low permeability fill (noted “Zone A”), and downstream and upstream shoulder with compacted rockfill without permeability requirement (noted “Zone Bii”). The embankment was subsequently raised using the downstream construction method, with Zone A fill forming the upstream slope and rockfill for the downstream embankment shoulder.

The TSF is currently in an active closure phase with construction of closure items ongoing. A tailings beach with a rehabilitation capping has been established against the tailings dam. The reservoir water is kept at approximately 200 m away from the tailings dam embankment. Once the closure works are complete and demonstrated to be functioning as designed, the facility can be considered as closed and in the post-closure phase.

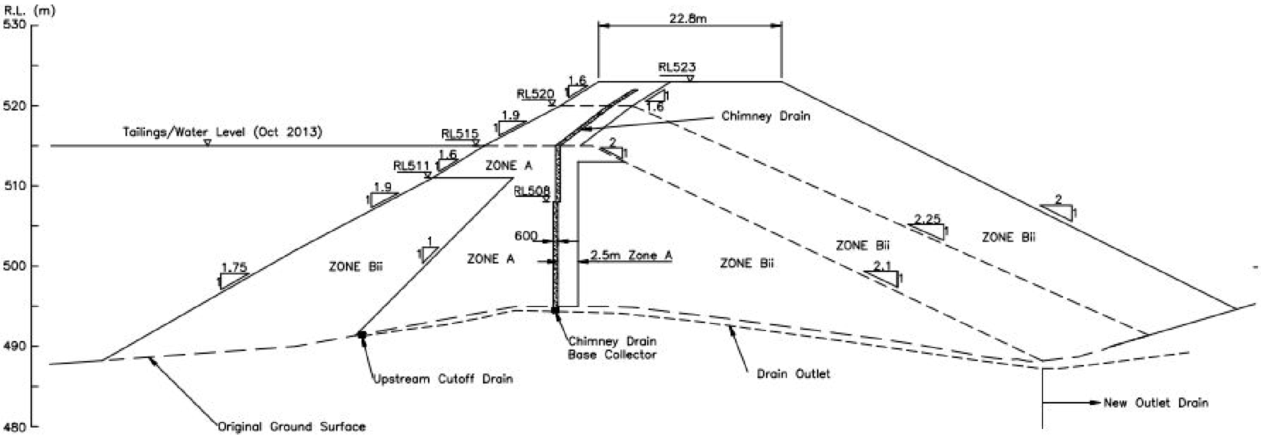

Figure 1: Typical cross section of the tailings dam embankment

3 RISK FRAMEWORK

The framework for dam safety management using risk to inform decisions involves three distinct components (FEMA, 2015). These components, each having their own purpose and function. They are:

- Risk analysis
- Risk assessment
- Risk management

Figure 2 shows how risk analysis, risk assessment, and risk management relate to each other. For risk analysis, the key activities are failure mode identification and risk estimation (assessing loading on the dam, structural response, consequences of breach, etc.). Risk assessment takes the outcomes from the risk analysis and evaluate the risks (i.e., probabilities of consequences). Decision making recommendations to reduce the risks can then be made through the insight gained from the risk assessment. Ultimately risk management is about decision making to manage the risk. For dams with high risks this is primarily about risk reduction. Risk communication, although not specifically identified in Figure 2, is a critical part of each component of risk management (FEMA, 2015). Risk may change throughout the lifecycle of a tailings dam and is re-assessed periodically or when there are material changes that may affect risk.

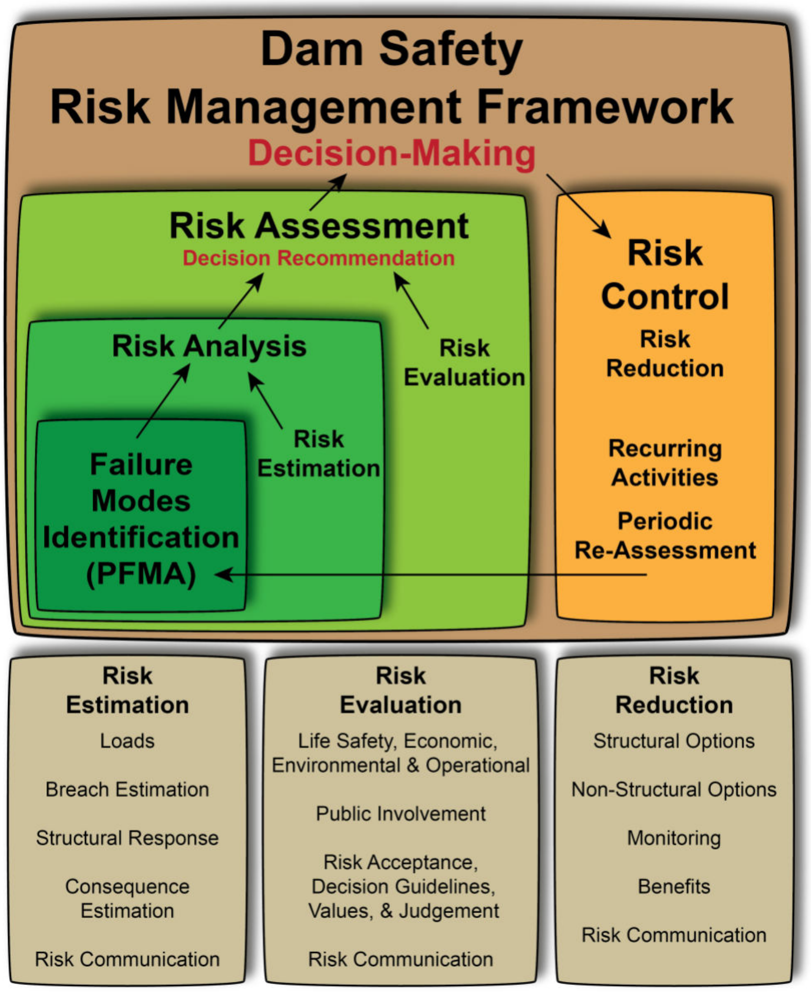

Figure 2: Dam safety risk management framework (adopted from FEMA, 2015)

4 RISK ANALYSIS

4.1 Failure modes and effect analysis

Risk analysis is the first step of risk management. Failure modes and effects analysis (FMEA), as a key activity of risk analysis, allows for the systematic identification and analysis of the different failure modes and their associated consequences. The procedures to conduct an FMEA followed the methodology as descripted in the studies of Schafer et al. (2021) for assessing geotechnical risks associated with tailings dam closure, including

- identification of key elements and functions,
- analysis of failure modes of the different elements considering both positive factors, i.e. less likely factors, and negative factors, i.e. more likely factors,
- assessment on the effects and consequences, i.e. whether a catastrophic failure could be induced.

The case study presented is for the potential failure mode of piping resulting from seismic induced downstream instability of the tailings dam embankment. Positive and negative factors were developed in a workshop environment and are summarised in Table 1.

Table 1: FMEA of the considered failure mode associated with seismic slope stability

Description: Seismically induced deformations and cracking of the tailings dam embankment leads to piping though the embankment, erosion, and release of contents

Element	**Positive Factors**	**Negative Factors**
Foundation	• Faults in the foundation are all very old and of Tertiary Age. • Construction photos of slush grouting during foundation preparation • GNS has assessed the potential for the fault displacement at the site and concluded that there are no recently active faults or shears and that all basement structures can be regarded as inactive with no evidence of either movements within the last 500,000 years.	• Potential of fissures within the foundation. • Should a major earthquake occur on nearby active faults then secondary faulting of up to 400 - 500 mm may occur on some basement faults in the foundation. Small 'sympathetic' displacements of possibly up to 100 mm may also occur on joints or minor shears. The secondary faulting hazard is regarded as low.
Drainage	• Embankment toe drain will collect seepage by-passing the chimney drain. • Non-linear time history analysis indicates strain accumulation along chimney drain is not notable.	• Potential blockage and/or breakage of chimney drain or breakage of the connection between the chimney drain and outlets due to shear displacement of embankment under earthquake. • Potential clogging of geotextile.
Embankment	• Wide embankment crest of 22.8 m to provide contingency. • Rockfill is less erodible. • Embankment fill has good compaction with quality control tests undertaken and documented during construction. • Dynamic analysis indicates: - potential cracking of embankment will be limited on downstream slope and downstream side of the crest, - induced deformation is unlikely to affect the low permeability zone, - Longitudinal cracks are expected to form predominantly on the downstream half.	• Increase of phreatic surface due to potential loss of drainage. • Zone A and Zone Bii embankment fill are not fully filter compatible. • Zone A and Type B drainage materials used in the drain outlets are not filter compactible. The control of piping into Type B material relies on geotextile separation between Zone A and Type B drainage materials.
Tailings beach	• Tailings beach keep the water away from the embankment. • Low permeability of tailings will reduce seepage of water.	• Liquefiable tailings.

4.2 Tailings dam breach analysis

The consequence of the potential failure mode of the tailings dam discussed above was estimated by undertaking a tailings dam breach analysis (TDBA). The TDBA was undertaken according to the CDA technical bulletin (CDA, 2021), with consideration of the tailings physical characteristics and rheology, topographic data and hydrologic data. The downstream inundation resulting from a dam breach flood was simulated, by modelling the tailings slurry as non-Newtonian fluids with defined yield stress and viscosity. The Population at Risk was estimated as 25 people and the Potential Loss of Life was estimated as four. Three houses may be damaged, and one house may be destroyed. Several roads, bridge and railway may be affected, including a section of State Highway. It could take up to three months to restore to operation. The natural environment may be heavily damaged, and the clean-up of sediments could be costly. A financial consequence of NZ$30M was estimated based on the assessments of consequences.

5 QUANTITATIVE RISK ASSESSMENT

Risk assessment is the process of examining the safety of a specific structure, making specific recommendations, and recommending decisions on a given dam or project using risk analysis, risk estimates, and other information that have the potential to influence the decision (FMEA, 2015). The assessment considers all factors, e.g. likelihood, consequences, cost, environmental impacts, etc. A qualitative risk assessment is first undertaken on the risks identified in the FMEA. Only those PFMs assessed as credible PFMs are carried forward to the risk assessment. The risks are evaluated based on the consequence and likelihood category in a risk matrix. A quantitative risk assessment is followed with the focus on the risks evaluated as “High” or “Extreme” in the qualitative assessment.

A quantitative risk assessment was undertaken associated with piping resulting from seismic induced downstream instability of the tailings dam embankment, as the risk was evaluated as “High” in the qualitative assessment. The quantitative assessment included creation of event trees to consider potential risk-drivers within the failure mode being assessed, loading frequencies (i.e. return periods of earthquake) and system response probabilities. The results of the assessment are compared with the ANCOLD limit of tolerability for existing dams (ANCOLD, 2022).

Event tree analysis is a commonly used approach for understanding, analysing, and communicating dam safety risk. An event tree is a visual representation of all events which can occur in a dam. Event trees begin with an initiating event (i.e. flood and earthquake) and depict the possible sequences of events, which can lead to a failure and the realization of consequences. It is an effective method of dissecting the operation into simple, but critical components (events) which can then be assigned probabilities of success or failure. The following sequence of events was applied in the event tree analysis:

- Earthquake event, with different loading frequency (Nodes: Normal, OBE and SEE),
  - Significant material strength loss (Nodes: Yes/No),
    - Deformation and/or instability (Nodes: Excessive, Moderate and Small),
      - Cracking induced damage (Nodes: Yes/No),
        - Scenario 1: Piping, breach and release of liquefied tailings,
          Scenario 2: Piping, breach and release of eroded tailings.

The probability of the last step of the above sequence was assessed via a subordinate event tree considering the sequence of events for embankment pipping. The probability of different scales of seismic induced deformation was assessed based on the method of Bray and Macedo (2019) and verified by a nonlinear time history analysis considering a number of ground motions with different intensity. The stability assessment has considered an elevated pore pressure condition within the embankment assuming loss of function of the chimney drain. The likelihood scale used to estimate probabilities at the other nodes of each event tree is based on the scheme in Table 2 (Barneich et al., 1996). It is a mapping scheme relating to probability of failure to objective information on the occurrence elsewhere of that type of failure. This method provided a repeatable basis of probability estimation (ANCOLD, 2022).

Table 2: Scheme relating to probability of failure (Barneich et al., 1996).

Description of Condition or Event	**Order of Magnitude Probability Assigned**
Occurrence is virtually certain.	1
Occurrences of the condition or event are observed in the database.	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

6 RESULTS AND DISCUSSION

6.1 Societal risk

The societal risk criteria for existing dams defined in ANCOLD guidelines is shown in Figure 3. The annual probability of catastrophic failure due to seismic induced slope instability estimated from the event tree analysis is 7.04E-12. It is the sum of the probability of the following four pathways in the event tree, and plots well below the limit of tolerability.

- SEE (1E-4) → Significant Material Strength Loss (Yes: 1E-2) → Excessive Deformation (Yes: 1E-2) → Cracking induced damage (Yes: 9E-1) → Piping, breach and release of liquefied tailings (Yes: 7E-4) = 6.13E-12
- SEE (1E-4) → Significant Material Strength Loss (Yes: 1E-2) → Excessive Deformation (Yes: 1E-2) → Cracking induced damage (Yes: 9E-1) → Piping, breach and release of eroded tailings (Yes: 9E-8) = 8.03E-16
- OBE (6.67E-3) → Significant Material Strength Loss (Yes: 1E-3) → Excessive Deformation (Yes: 1E- 3) → Cracking induced damage (Yes: 9E-1) → Piping, breach and release of liquefied tailings (Yes: 1.51E-4) = 9.07E-13
- OBE (6.67E-3) → Significant Material Strength Loss (Yes: 1E-3) → Excessive Deformation (Yes: 1E- 3)→ Cracking induced damage (Yes) → Piping, breach and release of eroded tailings (Yes: 7.13E-7) = 4.28E-15

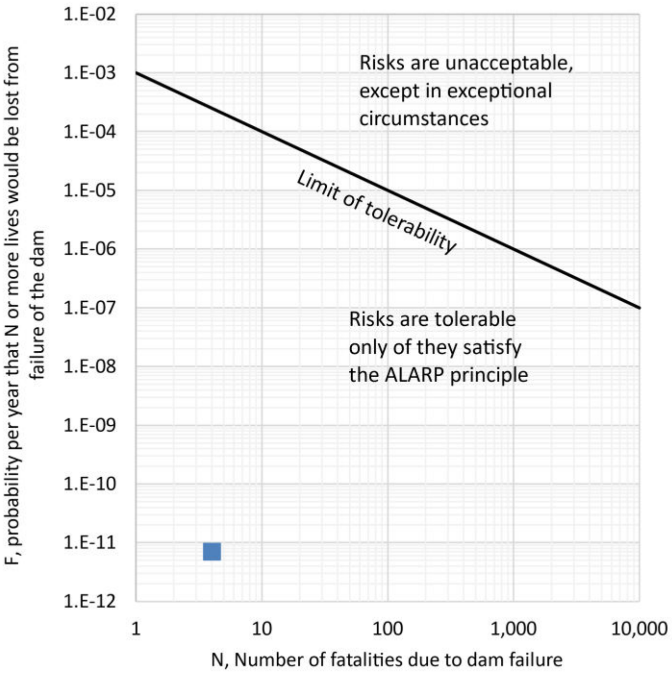

Figure 3: Assessment against the limit of tolerability defined in ANCOLD Guidelines.

6.2 ALARP Demonstration

ANCOLD (2022) provides guidance that the ALARP principle should be applied indefinitely below the limit of tolerability as the primary basis for determining the tolerable risk in any particular case. Risks are considered to be ALARP if the risks are reduced to the extent that the sacrifice (i.e. cost and time) in implementing further risk reduction is grossly disproportionate to the level of risk reduction achieved. In a cost-benefit analysis, if the cost of new control to benefit ratio is greater than the disproportion factor, then the new control can be considered not worth doing for the risk reduction achieved. The disproportionate factor is determined based on the estimated Potential Loss of Life and risk level in terms of orders of magnitude below the limit of tolerability using the methodology specified in the ANCOLD guidelines (2022). The potential failure mode is assessed at least seven orders of magnitude below the limit of tolerability, the disproportion factor is assessed to be 1.0, i.e. the cost of new control will need to be equal or lower than the benefit to be considered worth doing.

A qualitative cost-benefit analysis is discussed below to demonstrate the requirement of additional controls to satisfy ALARP.

- A large buttress fills at the downstream toe of the tailings dam embankment would have improved the stability (i.e., increase the Factor of Safety) and reduce the potential co-seismic deformation under strong earthquakes. It would reduce the probability of failure associated with piping. However, it would cost hundreds of thousands, and require clearance of additional forest area. Buttressing is unlikely to make a notable improvement to the earthquake or piping resilience of the embankment, as the existing probability of failure is very low. Therefore, a buttress is assessed as not being required under the ALARP principle.
- A new standpipe piezometer is recommended to be installed in Zone Bii of the downstream shoulder of the embankment. In the long term the existing vibrating wires piezometer can fail and will be difficult to replace. Without these piezometers the development of adverse conditions within the embankment will not be identified. The new standpipe piezometer can be manually dipped or with remote monitoring setup. The proposed standpipe piezometer has a relatively low cost of installation and maintenance

compared to the consequence of failure. It can assist the early detection of a potential failure mode, reduce uncertainty around the phreatic condition in the embankment, and increase the likelihood of successful intervention. Having certainty on the phreatic surface within the embankment has benefits when classifying an incident in response to an emergency.

7 CONCLUSIONS

The paper presents a case study of quantitative risk assessment of the potential failure mode of tailings dam due to piping induced by seismic slope instability. The event tree analysis indicates the probability of this potential failure mode plots well below the limit of tolerability. The ALARP principle can be achieved by additional monitoring.

The risk assessment of this case was undertaken in a workshop environment with the involvement of design engineers, representatives of the dam owner, operational staffs, and the construction manager. The workshop provided an opportunity to share knowledge of the project, so that all personnel involved were well informed and had a good understanding of the function of the tailings dam features. Quantitative risk assessment is a useful tool to identify, evaluate and inform decision for risk management. The process allows for input from various stakeholders and the results form the basis for continued discussion and communication, which enable the risks associated with dam safety to be managed to an acceptable level. The methodology used in this case study can also be applied on other high-risk project to inform engineering decision making.

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