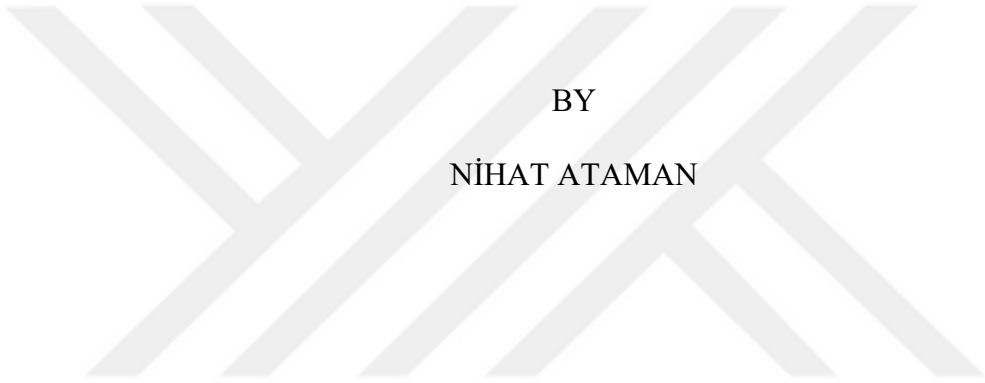


COMBINED RISK ASSESSMENT OF MULTIPLE TAILINGS DAMS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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Approval of the thesis:

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ABSTRACT

COMBINED RISK ASSESSMENT OF MULTIPLE TAILINGS DAMS

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Failures of tailings dams pose a significant threat to public health and safety, as well as to social and economic life and the environment. While studies on the risk assessment of traditional water storage dams are well established, the literature on the risk assessment of tailings dams is relatively new. In particular, the assessment of risks posed by multiple tailings dams is lacking. Current risk assessment approaches typically focus on the potential consequences of a single dam failure downstream.

This thesis study aims to develop a comprehensive methodology for assessing the combined risk from multiple tailings dams located upstream of a settlement. The proposed approach shifts the focus of the assessment from a single dam to the potentially affected community (settlement). In the event of a dam failure, the impacts on human health, social and economic life and the natural environment are taken into account and the total consequence of the event is determined by combining these different impacts.

The thesis presents an innovative approach to assess the failure potential of tailings dams in two main phases: active life (operation or deposition) and passive life (post-closure or abandonment), including management factors. A further significant contribution of the study is the development of a system dynamics model that

facilitates a time-dependent evaluation of risk levels, incorporating the complex and dynamic interactions present within the failure potential and consequence models. This model incorporates elements that are frequently overlooked in conventional risk assessments, such as significant health concerns and social interactions.

The application of the developed combined risk model to a hypothetical scenario and the 1985 Stava tailings dam disaster in Italy demonstrates that the proposed model more accurately predicts the risk faced by a downstream community. It is therefore anticipated that this thesis will make a substantial contribution to the literature on the risk assessment of tailings dams.

Keywords: Tailings Dam, System Dynamics, Risk Assessment, Risk Body, Combined Risk

ÖZ

BİRDEN ÇOK ATIK BARAJININ BİRLEŞİK RİSK DEĞERLENDİRMESİ

Ataman, Nihat
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Tez Yöneticisi: Doç. Dr. Onur Gölbaşı

Temmuz 2025, 203 sayfa

Maden atıklarının depolandığı atık barajı yıkılmaları, halk sağlığı ve güvenliği, sosyal ve ekonomik yaşam ile çevre üzerinde önemli tehditler oluşturmaktadır. Geleneksel su depolama barajlarının risk değerlendirmesi üzerine yapılan çalışmalar eskiye dayansa da atık barajlarının risk değerlendirmesi literatürü nispeten yenidir. Özellikle, birden fazla atık barajının yol açtığı risklerin değerlendirilmesinde belirgin bir boşluk bulunmaktadır. Mevcut risk değerlendirme yaklaşımları genellikle tek bir baraj yıkıldığında mansap üzerindeki potansiyel sonuçları değerlendirmeye odaklanmaktadır.

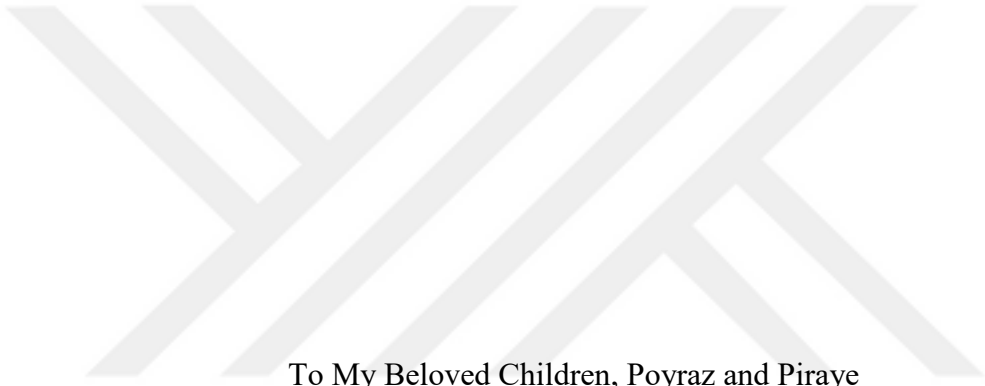
Bu tez çalışması, bir yerleşim yerinin mansabında yer alan birden çok atık barajından kaynaklanan birleşik riskin değerlendirilmesine yönelik kapsamlı bir metodoloji geliştirmeyi amaçlamaktadır. Önerilen yaklaşım, değerlendirmenin odağını tek bir barajdan, potansiyel olarak etkilenecek olan topluluğa (yerleşim yerine) kaydırmaktadır. Baraj yıkılması durumunda insan sağlığı, sosyal ve ekonomik yaşam ile doğal çevre üzerindeki etkiler dikkate alınmakta ve olayın toplam sonucu bu farklı etkilerin bir araya getirilmesiyle belirlenmektedir.

Tez, atık barajlarının yıkılma potansiyelini aktif ömür (işletme veya depolama) ve pasif ömür (kapatma sonrası veya terk edilme) olmak üzere iki ana aşamada

değerlendirip yönetim faktörlerini de içerecek şekilde yenilikçi bir yaklaşım sunmaktadır. Çalışmanın önemli bir diğer katkısı, yıkılma potansiyeli ve sonuç modellerindeki karmaşık ve dinamik etkileşimleri dikkate alarak risk seviyelerinin zamana bağlı olarak değerlendirilmesini sağlayan bir sistem dinamiği modelinin geliştirilmesidir. Bu model, ciddi sağlık sorunları ve sosyal etkileşimler gibi geleneksel risk değerlendirmelerinde sıklıkla göz ardı edilen unsurları da içermektedir.

Geliştirilen birleşik risk modelinin varsayımsal bir senaryoya ve 1985 yılında İtalya'da gerçekleşen Stava maden atığı barajı felaketine uygulanması, önerilen modelin mansaptaki bir topluluğun karşı karşıya olduğu riski daha doğru bir şekilde tahmin ettiğini göstermektedir. Böylece bu tezin, atık barajlarının risk değerlendirmesi literatürüne önemli katkılar sağlaması beklenmektedir.

Anahtar Kelimeler: Atık Barajı, Sistem Dinamiği, Risk Değerlendirmesi, Risk Kütlesi, Birleşik Risk



To My Beloved Children, Poyraz and Piraye

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I am also immensely grateful to the expert panel who generously contributed their time and knowledge to the survey phase of this research. Their invaluable insights and feedback were invaluable. Their expertise was an indispensable component of this study's success.

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This thesis is also a testament to the profound support I've received from my family. To my children and my sister, your boundless love, understanding, and unwavering belief in my abilities provided the strength and motivation needed to overcome every obstacle. Your sacrifices, both big and small, did not go unnoticed and are deeply appreciated. This achievement is as much yours as it is mine.

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CHAPTER 1

INTRODUCTION

1.1 Background

Mineral processing of hard rock metal ores (e.g., gold, copper, lead, zinc, uranium) and industrial mineral deposits (e.g., phosphate, bauxite) entails size reduction and separation of the constituent minerals. The crushed material, after passing through the processing plant to extract the desired product, is discharged as tailings, which represent the waste material from the mineral processing operations. In many regions globally, tailings constitute the largest volume of mine waste (ICOLD, 2001).

Various methods for the handling and storage of tailings have been employed, including riverine and submarine disposal, wetland retention, backfilling, dry stacking, and the containment of tailings behind impoundments, commonly referred to as tailings dams or tailings storage facilities (TSFs) (Lottermoser, 2010).

Several studies have been conducted to compile data on tailings dam failures, identify their causes, and discern underlying trends (Azam & Li, 2010; Rico *et al.*, 2008; UNEP, 1996; USCOLD, 1994). However, no single regulatory body systematically records comprehensive statistics on tailings dam failures. Moreover, the existing data do not facilitate comparisons between the number of tailings dam failures and the total number of tailings dams constructed in specific regions or time periods (ICME & UNEP, 1998).

The failure mechanisms of tailings dams, the flow characteristics of tailings, and the consequences of such failures have been extensively studied (Benito *et al.*, 2001; Blight, 1997; Blight & Fourie, 2005; Fourie, Papageorgiou, and Blight, 2000; Gallart

et al., 1999; Jeyapalan, Duncan and Seed, 1983; Krausmann and Mushtaq, 2008; Neuhold and Nachtnebel, 2011; Pastor et al., 2002; Van Niekerk & Viljoen, 2005).

Risk-based analysis was first applied in 1976 to assess the failure of the Teton Dam in the United States. In 1994, the Australian National Committee on Large Dams (ANCOLD) developed risk assessment guidelines, which were subsequently revised in 2003. Similarly, the International Commission on Large Dams (ICOLD) introduced its own risk assessment guidelines in 1998, which provided a technical framework for risk-based analysis in dam safety evaluations (Zhong, Sun, & Li, 2011). Prior to these developments, many experts and researchers regarded tailings dams as fundamentally different from traditional dams due to their simpler design, extended construction periods, and lack of water storage capacity. However, significant disasters resulting from accidents involving large tailings ponds have increasingly drawn attention to the need for enhanced risk awareness and management (Wang et al., 2011).

Following recent accidents at tailings facilities, such as the Baia Mare disaster in Romania and the Aznalcóllar incident in Spain, which resulted in significant risks to both the environment and human life, the European Union funded two major projects: Tailsafe and e-EcoRisk. The general objective of Tailsafe is to develop and apply methods of parameter evaluation and measurement for the assessment and improvement of the safety state of tailings facilities, with particular attention to the stability of tailings dams and slurries, the special risks inherent when such materials include toxic or hazardous wastes, and authorisation and management procedures for tailings facilities. “A Regional Enterprise Network Decision-Support System for Environmental Risk and Disaster Management of Large-Scale Industrial Spills” (e-EcoRisk) project use the catastrophic rupture or overflow of mine tailings dams as the basis for formulating and structuring of the information management and decision-support system, with particular attention being paid to the requirements of environmental and civil protection agencies and relevant EU policies, legislation, and regulations. e-EcoRisk aimed at development of innovative dam break and

spatial-temporal dam break and surface discharge models for analysing different environmental risk scenarios with respect to potential mine tailings dam spills.

Failures of tailings dams have resulted in significant threats to public health and safety, economic stability, and the environment. As a result, the safety of tailings dams has become a critical area of research. While studies on risk assessment for conventional water retention dams date back to 1976, literature on the risk assessment of tailings dams remains relatively recent, and comprehensive assessments of the overall risks caused by individual tailings dams are notably absent. In addition, cumulative risk assessment of multiple tailings dams with shared risk bodies has not been observed in the literature.

1.2 Problem Statement

Tailings dams are critical hydraulic structures designed to store large volumes of semi-fluid tailings and supernatant water. Their effective performance, both during mining operations and long after decommissioning, is essential for ensuring the safety of nearby communities and the protection of the downstream environment (Lo & Kloth, 1996). Catastrophic release of substantial quantities of tailings could result in long-term environmental damage, incurring significant cleanup costs (Cambers & Higman, 2011).

Tailings storage facilities typically represent the most substantial environmental liability associated with mining operations (Martin, et al., 2002). Failures of tailings dams have subjected the mining industry to growing pressure and scrutiny regarding its environmental practices, particularly the safety of tailings impoundments (Martin et al., 2002). Tailings dams have failed at a significantly higher rate than water supply reservoir dams (Cambers & Higman, 2011). Over the past century, the failure rate of tailings dams is estimated at 1.2%, which is more than two orders of magnitude greater than the failure rate of conventional water retention dams, reported to be 0.01% (ICOLD, 2001). Failures of tailings dams worldwide have led

to flooding of communities, resulting in fatalities, injuries, and significant loss of property and production. Recent disasters involving the release of tailings effluents and solids from containment facilities have increased awareness of the risks associated with tailings storage and containment (Bruce, Logue & Wilchek, 1997).

Some failures may occur despite the application of good engineering practices and strict adherence to engineering principles; however, risk assessment methodologies may help further reduce failure rates (Bruce et al., 1997). Therefore, effective risk assessment and management are essential to ensuring the safe operation of tailings dams. A variety of risk assessment approaches are available to the mining industry but they are all focused on the risk from a single tailings dam.

The Mining Association of Canada (MAC) has published a guide for the management of tailings disposal facilities (MAC, 2017). This guide identifies four phases in the life cycle of a tailings impoundment: design, construction, operation, and closure. The MAC guidelines recommend conducting a risk assessment for each of these phases but it does not suggest any methodology covering active or inactive life of tailings storage facilities.

Similarly, a risk evaluation methodology has been implemented at the national level for tailings dams in Romania after the Baia Mare tailings dam disaster in 2000 (Mara et al., 2007). However, risk assessment in a local level, especially focusing on small communities, is necessary to enhance the social acceptance and liability of a mining activity.

The European Union mandates risk assessments when classifying waste facilities. The Directive on the Management of Waste from Extractive Industries, enacted in 2006 (Directive 2006/21/EC), specifies that "A waste facility shall be classified under Category A if a failure or improper operation, such as the collapse of a heap or the bursting of a dam, could lead to a major accident. This classification is based on a risk assessment that considers factors such as the current and future size, location, and environmental impact of the waste facility." However, the Directive

does not provide any methodology that inclusively estimates the current and future risks.

There is an absence of reliable information regarding tailings storage facilities in Türkiye, or the inventory of such facilities is inaccessible to the public. While many tailings dams are either under construction or planned in Türkiye, there is a lack of comprehensive risk assessments at any stage of the tailings dam life cycle. Risk evaluations are typically limited to preliminary qualitative assessments in Environmental Impact Assessment (EIA) reports, where individual projects are assessed, but cumulative effects are often ignored.

Recent failures of three tailings dams have attracted significant public attention in Türkiye. In September 2009, the Melet River, a primary drinking water source for Ordu province, was contaminated by tailings from a metallic ore processing plant following the failure of a tailings dam after heavy rainfall. In May 2011, an intermediate dike of a tailings dam containing silver leach tailings failed and all the tailings held back by the outer perimeter dike in Kütahya province. These incidents underscored the risks associated with tailings storage facilities. More recently, in November 2021, the failure of Tailings Dam No. 2 in the Şebinkarahisar district of Giresun province led to the release of tailings into Dam No. 1, which subsequently discharged into the Darabul Stream, ultimately reaching Kılıçkaya Dam, located 5 km downstream.

The existing literature highlights a significant gap in cumulative risk assessments of multiple tailings dams located within a river basin. Furthermore, the available risk assessment methodologies are often simplistic and linear, failing to account for the dynamically changing and interactive nature of risk factors. However, the consequences and failure probabilities of tailings dam failures can evolve over time and require consideration within more complex and dynamic frameworks.

1.3 Objectives and Scopes of the Study

The current thesis study aims to develop a methodology for assessing the combined risk associated with multiple tailings dams. Combined risk will be analysed as a function of the individual risks posed by each tailings dam. Accordingly, the primary objective of this study is to establish a framework for evaluating combined risks to a community downstream of multiple tailings dams. The developed methodology will also be applicable to single tailings dam scenarios.

The methodology will enable the assessment of the collapse of tailings dams, which, despite comparatively their low probability, could result in catastrophic outcomes. This approach focuses specifically on these rare but high-impact events, while excluding events such as the seepage of chemicals or leachates from tailings dams, which, although more likely, do not lead to catastrophic consequences.

1.4 Research Methodology

The study methodology entails successful implementation of the following steps:

- i. ***Literature Review:*** A thorough review of the existing literature on risk assessment methodologies and related factors for tailings dams will be undertaken.
- ii. ***Determination of the Extent of the Risk Body (Potential Inundation Areas, Coverage area):*** This part will outline a methodology for assessing how a dam failure may propagate throughout its basin, resulting in varying areal range of damage, utilizing third-party software for analysis. To assess potential inundation (coverage) areas, a numerical flow model capable of accounting for high sediment concentration floods is essential. This section will provide guidance on the selection and application of an appropriate model for directly simulating tailings, such as FLDWAV, FLO-2D, HEC-RAS.

- iii. ***Development of the Consequences Concept Model:*** The failure of tailings dams results in a wide range of diverse consequences. A conceptual model for evaluating the consequences of tailings dam failure will be developed, addressing four key dimensions: human health, economic loss, social impacts, and environmental effects. The severity of these consequences will be influenced by coverage area, flow characteristics, tailings properties, and receptor vulnerability, with each one assigned varying weights based on its relative importance.

The Human health aspect will address the loss of life, injuries, disabilities, and illnesses, which are influenced by the severity of the failure and the level of preparedness.

Social and Economic Life is assessed through the evaluation of property damage, infrastructure and facility destruction, and income loss, all of which reflect the failure's impact on the economy. It also will consider factors such as forced evacuations, loss of houses, and the disruption of public services, using a displacement index. It also includes the measurement of social unrest, considering trauma, damage to infrastructure and facilities, and the loss of cultural heritage.

Finally, the Environmental aspect will examine soil contamination, damage to biodiversity, impacts on both aquatic and terrestrial ecosystems, and the quality of water, in order to assess the environmental consequences of a tailings dam failure.

- iv. ***Development of the Failure Potential Conceptual Model:*** This section will present a conceptual model for estimating the potential of failure of tailings dams, considering five key factors: Four failure modes and a management factor.

Failure modes includes overtopping, slope instability, internal erosion, and foundation failure.

Management Factors will be incorporated to assess failure probability, including regulatory compliance, external audits, monitoring practices, closure plans, capital investments, safety management, emergency preparedness, training of workers and safety culture, and personnel qualifications and experience.

- v. ***Conducting Expert Panels to Establish Dependencies in the Consequences and Failure Potential Conceptual Models:*** Both conceptual models developed to assess the consequences and probability of failure of tailings dams involve numerous complex and dynamic equations. Some of these equations will be evaluated using indices and scoring rubrics. Based on this framework, expert groups will be selected to assess the dependencies between mutually dependent factors. The candidate expert groups for the panels are as follows:

- Consultants
- Operators
- Regulators
- Academia
- Non-Governmental Organizations

- vi. ***Development of a System Dynamics Model for Combined Risk Assessment of Multiple Tailings Dams:*** Considering the factors and interactions outlined in the conceptual models of consequences and failure potential, a system dynamics model will be developed. This model, supported by a computational framework, will be capable of assessing the combined risks associated with one or more tailings dams.

The combined risk assessment in this study is based on the approach developed by the United States Environmental Protection Agency (USEPA), which defines cumulative risk as the combined risks resulting

from aggregate exposures to multiple agents or stressors. In the context of this study, the stressors are the individual tailings dams. The combined risk assessment will focus on communities living downstream of the tailings dams that may be affected by potential risks. Each community, along with its socio-economic conditions and environment, is considered a risk body. Each risk body is separated into risk segments according to exposure conditions, and the risks from these segments will be aggregated to calculate the overall combined risk.

- vii. ***Verification and Validation of the System Dynamics Model:*** The developed model will be applied to a hypothetical case study to assess its strengths and limitations. Once the model has been verified and calibrated using the hypothetical case the model will be implemented for the area affected by the Stava Dam collapse. In 1985, two tailings dams above the village of Stava in Italy collapsed, resulting in the deaths of 268 people and the destruction of 63 buildings. Since the consequences of the event are well-documented, this case will allow for the validation of the model's effectiveness.

1.5 Expected Contributions of This Thesis

Risk management processes for tailings dams typically focus on the risks associated with individual facilities. This approach is suitable when a single mining operation is located in a remote area. However, when multiple tailings dams are situated near communities, it becomes essential to consider combined risks. The proposed thesis aims to develop a methodology for assessing the combined risk associated with multiple tailings dams. Following contributions to enhance risk assessment literature and tailings dam management processes are expected:

- i. Life loss and fatalities are included in risk assessment processes but serious health conditions such as prolonged illnesses or disabilities induced by

tailings dam failure are excluded. Consequence assessment method utilised in this study additionally includes serious health impacts.

- ii. In conventional risk assessment methods of dam failures or collapses, economic losses are estimated but social impacts are underestimated or ignored. In this thesis study social disturbance are also qualitatively estimated.
- iii. Consequence assessment model in this study broadens the pollution based environmental impact assessment, that is utilized in conventional risk assessment models, and includes some ecosystem services which are generally ignored.
- iv. This study integrates management (human) factors to failure potential of tailings dam, which are often not included in risk assessment processes.
- v. Proposed risk assessment model contains time dependent and interdependent variables; therefore, the model integrates the system dynamic approach to risk assessment of tailings dams.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a background information and comprehensive literature review on tailings dams and risk assessment. Firstly, some background information on tailings dams will be provided to reveal the risks triggered by the tailings dams. Secondly, risk assessment and its applications to tailings dams will be discussed. Thirdly, operating standards and best practices related to tailings dam risk assessment will be presented. Lastly, previous literature studies on the improvement of risk assessment of tailings dams are comparatively discussed to highlight the novelty of the current thesis study.

2.2 Mine Tailings

On a global scale, the mining industry provides direct employment for over 40 million people and indirect financial effects for around 200–250 million people (Kossoff et al. 2014). Despite its observable benefits to varying sectors, national gross products, and global industrialization, the mining industry produces enormous volumes of waste, measured as several thousand million tonnes per annum, close to other earth-shaping geological processes (Kossoff et al. 2014). Over 99% of the excavated ore material for low-grade deposits is expected to become tailings following mineral processing stages. In brief, it can be stated that the main waste stream in mining is tailings, presenting the most voluminous waste at mine sites (Lottermoser, 2010).

Generally mixing with sand and silt together with unrecoverable minerals, chemical reagents, and process water, tailings mainly consist of the processed rock or soil left from separating the valuable commodities from their hosted rock or soil (ICMM, UNEP & PRI, 2020). The facilities to handle and store tailings, composed of riverine disposal, submarine disposal, wetland retention, backfilling, dry stacking, and storage behind impoundments, are commonly called Tailings Storage Facilities (TSFs) or tailings dams (Lottermoser, 2010).

2.3 Construction Types of Tailings Dams

Various dams or embankments are constructed to retain the stored tailings at mining sites. International Commission on Large Dams defines tailings dams as dams constructed of mill tailings, mine wastes, or earth of rock fill to retain tailings slurry or slurry water for reclamation (ICOLD, 1982). Storage capacities of these dams are increased in time without interrupting the mining activities. Therefore, their construction aspects can differ from regular water-retaining dams that require a finalized construction before becoming operational. Tailings dams can be constructed as i) upstream, ii) centerline, iii) downstream, iv) a variation of water-retention dam, or v) a combination of any of these methods (Figure 2.1 and Figure 2.2).

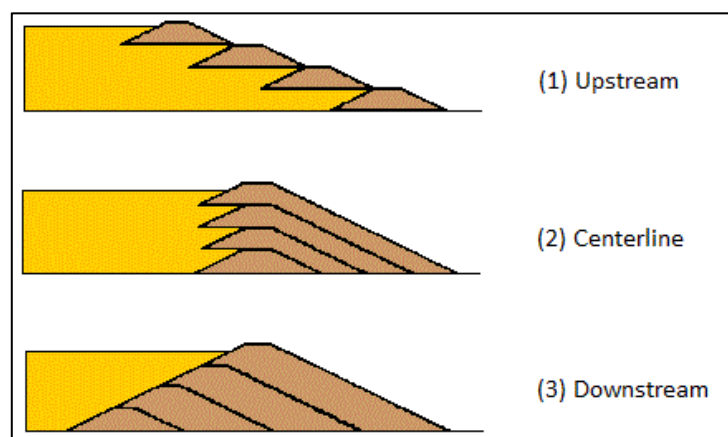


Figure 2.1: Types of Sequentially Raised Tailings Dams (modified after Vick, 1990)

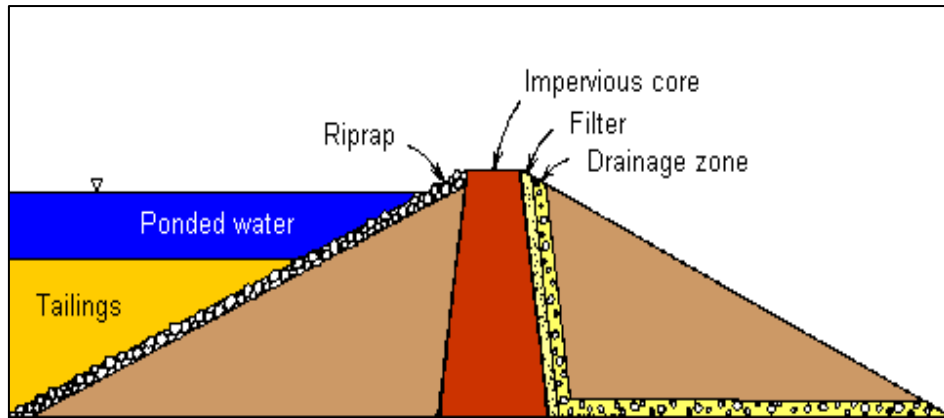


Figure 2.2: Water-Retention Type Dam for Tailings Storage (Vick, 1990)

Design, construction, operation, and closure of tailing dams have some fundamental differences from conventional water storage dams (Table 2.1).

Table 2.1 Comparison of Tailings and Water Dams (Benckert & Eurenus, 2001)

	Tailings Dam	Water Dam
Design Objectives	Contain wastes from mineral processing (tailings) and some water (or saturated tailings) in a safe, stable and environmentally acceptable manner.	Safely contain and control water for any purpose.
Engineering Design Criteria	Static and seismic stability. Hydrology based on downstream flood, environmental risk and process needs.	Static and seismic stability. Hydrology based on downstream risk.
Environmental Criteria	Minimize environmental impact to an acceptable level throughout construction, operation and closure and minimize emissions to the surrounding environment throughout operation and after closure.	Minimize environmental impact.
Construction	Staged construction during operation to suit storage requirements.	Single construction phase
Operation	Ongoing design, construction, and storage control to meet waste disposal, environmental, and flood control requirements.	Reservoir level operation.
Closure	Closure when mineral extraction/processing ceases to create a safe and stable structure and an environmentally sustainable closure solution for thousands of years.	No specific closure requirements unless breaching is required for environmental reasons.

Construction type is affected by the following factors (Benckert & Eurenus, 2001):

- i. Tailings characteristics and mill output
- ii. Site characteristics such as topography, hydrology, geology, groundwater, seismicity, and available material
- iii. Disposal methods

Comparative evaluations of the dam types can be investigated in Table 2.2. It should be noted that every tailings dam is unique due to various factors, including the nature of the land and the tailings themselves (Van Niekerk & Viljoen, 2005).

Table 2.2 Comparison of Tailings Dam Types (Vick, 1990).

	Water Retention	Upstream	Downstream	Centerline
Mill Tailings Requirements	Suitable for any type of tailings	At least 40-60% sand in whole tailings. Low pulp density desirable to promote grain-size segregation	Suitable for any type of tailings	Sands or low-plasticity slimes
Discharge Requirements	Any discharge procedure suitable	Peripheral discharge and well-controlled beach necessary	Varies according to design details	Peripheral discharge of at least nominal beach necessary
Water Storage Suitability	Good	Not suitable for significant water storage	Good	Not recommended for permanent storage. Temporary flood storage acceptable with proper design
Seismic Resistance	Good	Poor in high seismic areas	Good	Acceptable
Raising Rate Restrictions	An entire embankment constructed initially	Less than 4.5 - 9 m/yr is most desirable. Greater than 15 m/yr can be hazardous	None	Height restrictions for individual raises may apply
Embankment Fill Requirements	Natural soil borrow	Natural soil, sand tailings, or mine waste	Sand tailings or mine waste if production rates are sufficient, or natural soil	Sand tailings or mine waste if production rates are sufficient, or natural soil
Relative Embankment Cost	High	Low	High	Moderate

The majority of the tailings dams were built several decades ago, and about 45% have been constructed with the upstream method, considered the least stable among the tailings dam construction methods (Wei et al., 2013).

2.4 Tailings Dam Failures

Many particular characteristics listed below make tailings dams more vulnerable to failures compared to water storage dams (Rico et al., 2008):

- i. Embankments formed by locally derived fills (soil, coarse waste, overburden from mining operations, and tailings).
- ii. Multi-stage raising of the dam to cope with the increase in solid material stored and effluent (plus runoff from precipitation) released,
- iii. The lack of regulations on specific design criteria,
- iv. Dam stability that requires continuous monitoring and control during the emplacement, construction, and operation of the dam,
- v. The high cost of remediation works after the closure of mining activities.

Geotechnical knowledge with engineering experience can enable safe tailings dams to be designed and constructed. Still, the current failure rate of tailings dams, an average of 1.7 each year during the past 30-year period, shows that this knowledge and experience has not been entirely applied in every stage (Penman, 2001).

Tailings dams have failed at a rate significantly higher than the failure rate for water supply reservoir dams (Cambers & Higman, 2011). Broadly, 2 to 5 out of the 3,500 tailings dams worldwide experience major failures yearly (Lemphers, 2010). The failure rate of tailings dams over the last one hundred years is estimated to be 1.2% (Azam and Li, 2010). It is more than two orders of magnitude higher than the failure rate of conventional water retention dams, which is reported to be 0.01% (ICOLD, 2001). Figure 2.3 shows that the three leading causes of tailings dam incidents are overtopping, slope instability, and earthquakes.

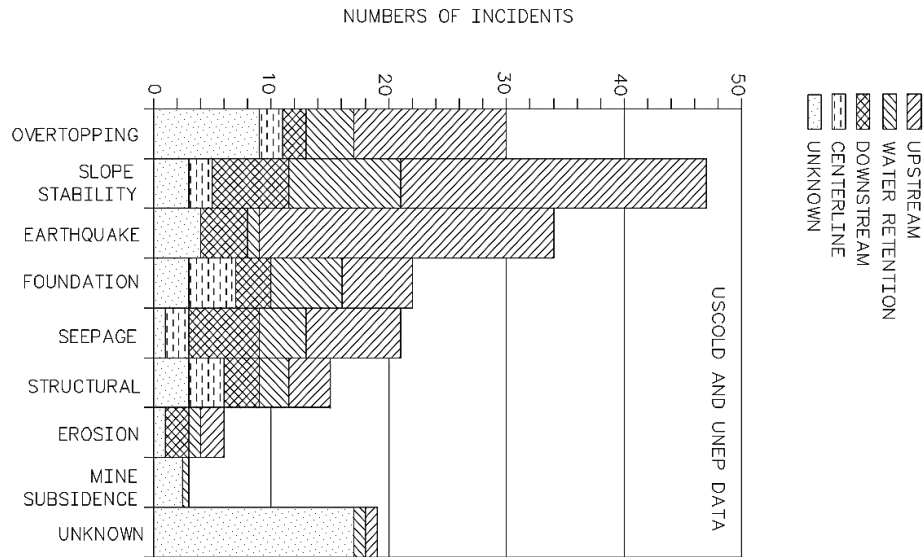


Figure 2.3: Causes of the Tailings Dam Incidents according to Dam Types (ICOLD, 2001)

Rico et al. (2008) classified the causes of tailings dam failures into eleven categories, where the major one is stated to be related to meteorological factors, such as heavy rain or heavy snow, accounting for 25% of worldwide cases and 35% in Europe (Figure 2.4).

Xin et al. (2011) state that the main factors affecting the deformation and stability of the tailings dams in China are the dam material composition, physical-mechanical properties, and the geometric parameters of dams (considering dam height, inside and outside slope ratio, dry beach length, warehouse inner water level, groundwater level elevation, and earthquake). Tailings dam failure modes were categorized as flood overtopping and the dam structural failure. Structural failure mode is evaluated regarding seepage failure, slope instability failure, and seismic failure; seismic failure mode can be further divided into seismic liquefaction failure and seismic instability failure (Xin, Xiaohu, & Kaili, 2011).

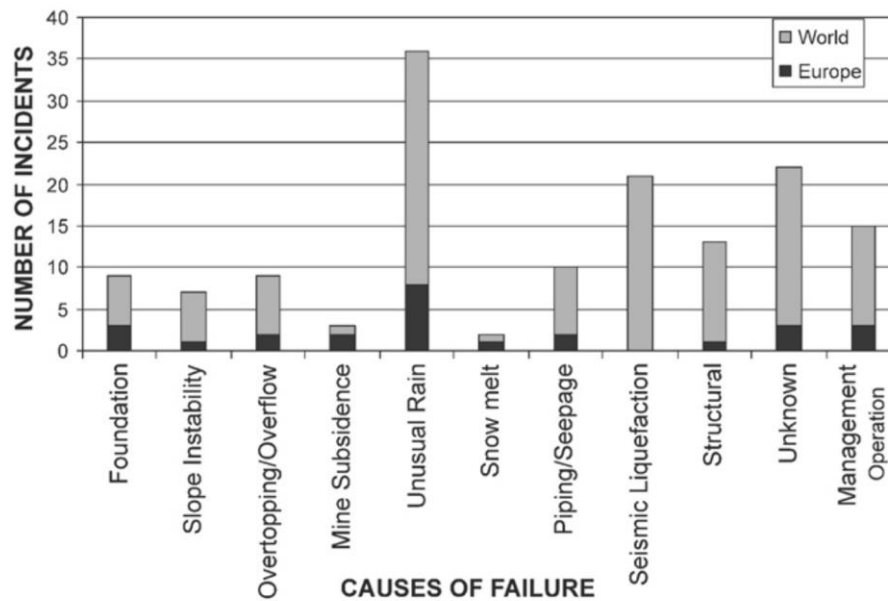


Figure 2.4: Number of Tailings Dam Incidents Worldwide and in Europe according to Failure Causes (Rico *et. al.*, 2008)

ICOLD classified the causes of tailings dam failures as follows (ICOLD, 2001):

- i. **Overtopping:** Overtopping occurs when a flood event exceeds the dam's capacity, leading to failure. This can result from extreme wind speeds or rainfall, blockage or damage to flood discharge and drainage structures, or a reduction in the dam's flood discharge capacity. These factors can cause water to impact the dam or raise the water level, ultimately resulting in dam failure. Flooding of tailings ponds is often caused by a complex interplay of factors, with precipitation being the primary driver. Contributing factors include the presence of impermeable dams, the aging of flood relief infrastructure, blockages, and structural damage. Thus, significant rainfall is a key precipitating factor in both flooding and subsequent dam failure.
- ii. **Foundation Failure:** Foundation failure occurs when excessive pressure or horizontal thrust damage the stability of the dam due to deformation or sliding. The primary causes of foundation failure include: 1) the presence of low-strength dam foundations, especially those built on karstic terrain, and 2) inadequate resistance to slippage in the dam foundation. Additional factors

such as foundation fracture, rock softening, or structural modifications can further reduce the foundation's ability to resist movement.

- iii. ***Earthquakes:*** Earthquakes contribute to tailings dam failure through three main mechanisms: liquefaction of tailings, weakening of the dam material, and destabilization of the dam structure. Earthquake-induced failures most commonly affect upstream-type dams, which are vulnerable due to factors such as high infiltration rates and insufficient seismic resistance.
- iv. ***Mine Subsidence:*** Tailings ponds built over underground mines are particularly prone to failure due to subsidence. The ground may not be able to support the weight of the settling or collapsing tailings pond, leading to dam failure.
- v. ***Structural Inadequacies and Inadequate/Failed Decants:*** Failures due to design errors or the malfunction of key components, such as decants (devices used to drain water from reservoirs), are common. Decant failure, in particular, is often a significant factor in tailings dam failures.
- vi. ***External Erosion:*** External erosion refers to damage caused by water flow at the structure's surface, while internal erosion involves damage to the foundation or beneath the surface. On a larger scale, rainfall can wash away soil, contributing to the failure of tailings dams.
- vii. ***Seepage and Internal Erosion:*** Seepage within the dam can cause deformation of tailings sand material through infiltration. In tailings dams, infiltration deformation may lead to the formation of a pipe surge within the dam body, which may cause cracking, localized collapse, and local instability of the dam slope. Such internal erosion can ultimately result in dam failure.
- viii. ***Slope Instability:*** The term 'dam destabilization' refers to damage resulting from a variety of factors, including tailing sand extrusion or construction defects, extreme precipitation, and other disturbances (excluding seepage). In most cases, deficiencies in the dam's structural strength or its resistance to

slippage alone are insufficient to cause failure. However, the appearance of cracks, bulges on the dam's surface, protrusions along the slope, subsidence of the dam's summit, or warping of the dike edge may serve as indications of damage.

The reports on tailings dam failures are observed to be incomplete and heavily biased. There is no complete worldwide database of all historical failures. The majority of tailings dam incidents remain unreported, especially in developing and undeveloped countries. Following an accident, accessing basic information regarding the tailings dam and its condition, such as dam height, tailings storage volume, tailings thickness, and water content, before the unwanted event is often challenging.

Piciullo et al. (2022) state that according to the different tailings dam databases since 1915 (ICOLD, WISE, World Mine Tailings Failures, CSP²), a total of 257 failures have been recorded with about 2650 fatalities and 250 million m³ of contaminated residues released to the environment. Almost 50% (115 million m³) of the contaminated residues was released after 2000, leading to around 640 fatalities (Piciullo et al., 2022).

As mentioned, tailings dam failures result from various causal mechanisms spilling out polluted water and tailings with different textural and physical–chemical properties, which may impact the downstream socio-economic activities and ecological systems (Rico et al., 2008). The failure of a tailings dam and the uncontrolled release of the impounded waste may have severe consequences for public safety, the environment, and the principal or subcontractor company. These consequences can be grouped into three major groups as follows (ICOLD, 2001):

- i. **Economic Consequences:** The financial burden of recovering or reconstructing the dam and impoundment and payments of unused workforce due to the inoperability of the dams can be evaluated under this group.

- ii. **Public Safety:** Public attention is increasingly focused on safety issues and hazards that may affect many people in a catastrophic event with lower acceptability than other unwanted events whose accumulated effects may negatively influence a limited number of individuals. Besides, exposure to unwanted events and a lack of risk awareness can impact communities more in case of failure since those people cannot expect to experience such an event.
- iii. **Environmental Damage:** The release of a substantial quantity of waste material that flows over a large area of surrounding ground may cause massive environmental damage, mainly if the waste is toxic. There are also risks associated with incremental events over a longer term, such as dust dispersion, groundwater contamination, landslides, or ground instability.

Table 2.3 gives examples of tailings dam disasters since 2015 and their highlighted consequences. Failures of three tailings dams have drawn public attention in Türkiye. In September 2009, Melet River, a primary drinking water source of Ordu province, was polluted by tailings from a metallic ore processing plant due to a tailings dam break after heavy rain.

In May 2011, an intermediate dike of a tailings dam containing silver leach tailings failed, and all the tailings were held back by the outer perimeter dike in Kütahya province. These cases highlighted risks induced by tailings storage facilities. In November 2021, Tailings Dam No.2 failed in the Şebinkarahisar district of Giresun province. The tailings flowed into Dam No. 1 and then into the Darabul Stream and reached Kılıçkaya Dam 5 km downstream.

Table 2.3 Selected Tailings Dam Disasters (Adopted from www.wise-uranium.org/mdaf.html, Retrieved, 10-11-2023)

Date	Location	Ore Type	Type of Incident	Impacts
2023, Sep. 30	Durango, Mexico	Lead, Silver, Zinc	Overflow of tailings dam after heavy rain.	The tailings flowed into Coluta River, then at least 8-10 km along the Tamazula River, threatening the drinking water supply in the area.
2022, Nov. 7	Shinyanga Province, Tanzania	Diamond	Tailings dam failure: The tailings escaped through an approx. 150 m wide breach of the eastern wall of the impoundment	The mud wave traveled over 8 km, covering 5.09 km ² , damaging 13 houses and farmland. Three injuries have been reported. About 115 citizens of Ngw'wanholo village have been severely affected.
2022, Sep. 11	Xhariep, Free State, South Africa	Diamond	Tailings dam failure	The mud wave traveled approx. 8.5 km, sweeping away and/or destroying 51 houses and affecting another 103, killing two persons, injuring another 76, and displacing more than 300. At least 500 animals have died.
2020, July 2	Hpakant, Kachin state, Myanmar	Jade	Waste heap failure after heavy rain	A heap of mining waste collapsed into a lake, triggering a wave of mud and water that buried many workers; at least 126 people were killed.
2019, Apr. 9	Muri, Jharkhand, India	Bauxite	Failure of red mud tailings pond	There was a spill of red mud over 35 acres and a nearby railway line; the number of casualties is still unclear.
2019, Jan. 25	Brumadinho, Minas Gerais, Brazil	Iron	Failure of tailings dam No. 1	The tailings wave devastated some parts of the mine; it then traveled approx. 7 km downhill, spreading to parts of the local community Vila Ferteco, near the town of Brumadinho; the slurry was then carried further by Rio Paraopeba; 267 people were killed, and several are still reported missing.
2017, Mar. 12	Hubei Province, China	Copper, Gold, Silver, Iron	A partial dam failure occurred at the northwestern corner of the tailings pond.	The tailings flooded the fish pond downstream of approx. 27 hectares. Two persons were reported dead, and one was reported missing.
2016, Aug. 8	Dahegou Village, Luoyang, Henan Province, China	Bauxite	Failure of a tailings dam holding about 2 million cubic metres of red mud	The village totally submerged in red mud, around 300 villagers evacuated, and many farm and domestic animals were killed
2015, Nov. 5	Germano mine, Bento Rodrigues, distrito de Mariana, Região Central, Minas Gerais, Brazil	Iron	Failure of the Fundão tailings dam due to insufficient drainage, leading to liquefaction of the tailings sands shortly after a small earthquake.	Slurry wave flooded the town of Bento Rodrigues, destroying 158 homes; at least 17 persons were killed, and two were reported missing; slurry polluted North Gualaxo River, Carmel River, and Rio Doce over 663 km, destroying 15 square kilometers of land along the rivers and cutting residents off from potable water supply; the damage is at least US\$ 6.7 billion.

2.5 Tailings Dam Classification

The classification of tailings dams exhibits significant variation on an international scale, influenced by the regulatory frameworks and guidance documents specific to each country. Two predominant practices have been identified in this regard: The first one is classification based on the potential consequences of failure. Second one is classification based on height and storage volume.

European Union classifies mining waste facilities in Category A/not Category A in accordance with the provisions in Annex III of Directive 2006/21/EC of 15th March 2006 on *the management of waste from the extractive industries*, which states that:

“A waste facility shall be classified under category A, if:

- a failure or incorrect operation, e.g. the collapse of a heap or the bursting of a dam, could give rise to a major accident, on the basis of a risk assessment considering factors such as the present or future size, the location and the environmental impact of the facility; or
- it contains waste classified as hazardous under Directive 91/689/EEC above a certain threshold; or
- it contains substances or preparations classified as dangerous under Directives 67/548/EEC or 1999/45/EC above a certain threshold.”

European Commission adopted a decision (2009/337/EC) on defining the criteria for classifying waste facilities. The Decision explains the details of the classification system. The Decision states that (EC, 2009):

“A waste facility shall be classified under Category A in accordance with 2006/21/EC if the predicted consequences in the short or the long term of a failure due to loss of structural integrity, or due to incorrect operation of a waste facility could lead to (Article 1):

- non-negligible potential for loss of life;
- serious danger to human health;
- serious danger to the environment.”

According to the Decision, the potential for loss of life or danger to human health is considered to be negligible or not severe if people other than workers operating the facility that might be affected are not expected to be present permanently or for prolonged periods in the potentially affected area. Injuries leading to disability or prolonged ill-health states shall be serious dangers to human health. The potential danger to the environment is considered to be not serious if:

- the intensity of the potential contaminant source strength decreases significantly within a short time;
- the failure does not lead to any permanent or long-lasting environmental damage;
- the affected environment can be restored through minor clean-up and restoration efforts

The Decision requires specific evaluations of the extent of the potential impacts in the context of the source-pathway-receptor chain in establishing the potential for loss of life or danger to human health or to the environment. If there is no pathway between the source and the receptor, the facility concerned is not classified as Category A based on failure due to loss of structural integrity or incorrect operation.

The Decision also determines the factors in assessing the potential of loss of life and danger to human health. It states that the following items should be evaluated at least (Article 5):

- (1) the size and properties of the facility, including its design;
- (2) the quantity and quality, including physical and chemical properties of the waste in the facility;
- (3) the topography of the facility site, including damping features;

- (4) the travel time of a potential flood wave to areas where people are present;
- (5) the propagation velocity of the flood-wave;
- (6) the predicted water or slurry level;
- (7) the rising rate of water or slurry levels;
- (8) any relevant, site-specific factors that may influence the potential for loss-of- life or for danger to human health.

In the case of loss of structural integrity for tailings dams, human lives are considered to be threatened where water or slurry levels are at least 0.7 m above the ground or where water or slurry velocities exceed 0.5 m/s (2009/337/EC).

Department of Minerals and Energy (DME) of Western Australia published a guideline in 1999 -*Guidelines on the safe design and operating standards for tailing storages* - using a hazard rating system to categorize tailings storage facilities (TSFs). The guideline classifies the TSFs using a hazard rating that recognizes the potential impact on the environment and any life, property, or mine infrastructure due to possible uncontrolled leakage or failure of the embankment.

The hazard rating is derived by considering (DME, 1999):

- The potential impact in terms of safety on any nearby community infrastructure and/or mining developments (including the TSF operator) in the event of either controlled or uncontrolled escape of material, seepage and/or abrupt failure of the TSF embankment at any stage in its life;
- The potential environmental impact in the event of either controlled or uncontrolled escape of material, seepage and/or abrupt failure of the storage embankment at any stage in its life;
- The potential impact in terms of economics on any nearby community infrastructure and/or mining developments (including the TSF operator) in the event of either controlled or uncontrolled escape of material, seepage and/or abrupt failure of the TSF embankment at any stage in its life; such

economic impacts should also consider the impact on the mining operation due to the temporary loss of the TSF resulting from the failure or uncontrolled escape of tailings from the facility.

The hazard ratings to be applied to TSFs in Western Australia are shown in Table 2.4 (Department of Mines and Petroleum, 2013).

Table 2.4 Hazard Rating of Western Australia

TYPE OF EFFECT	HAZARD RATING		
	High	Significant	Low
Uncontrolled Releases or Seepage			
Loss of human life	Location such that contamination of water supply likely to be used for human consumption and consumption of the contaminated water is expected.	Location less critical but contamination of a water supply likely to be used for human consumption and consumption of the contaminated water is possible	No contamination of a water supply likely to be used for human consumption expected.
Loss of stock	Location such that contamination of a water supply likely to be used for stock consumption and consumption of the contaminated water is expected.	Location less critical but contamination of a water supply likely to be used for stock consumption and consumption of the contaminated water is possible but not expected.	No contamination of a water supply likely to be used for stock consumption expected.
Environmental damage	Location such that damage to an environmental feature of significant value is expected.	The significance of the environmental feature is less or damage is possible but not expected.	No environmental features of significance or no damage expected.
Embankment Failure			
Loss of human life	Loss of life expected because of community or other developments.	No loss of life expected, but the possibility recognized. No urban development and no more than a small number of habitable structures downstream.	No loss of life expected.
Direct economic loss	Severe economic loss such as serious damage to communities, industrial, commercial or agricultural facilities, important utilities, mine infrastructure, the storage itself or other storages downstream.	Appreciable economic loss, such as damage to secondary roads, minor railways, relatively important public utilities, mine infrastructure, the storage itself or other storages downstream.	No significant economic loss, but possible limited damage to agricultural land, minor roads, mine infrastructure, etc.
Indirect Economic Loss	Storage essential for services and repairs not practicable.	Repairs to storage practicable.	Repairs to storage practicable. Indirect losses not significant.

DME guideline uses the hazard rating system in Table 2.4 together with the size of the facility to define three categories of TSF for which varying levels of detailed study and justification of design, operating procedures, and rehabilitation measures are required. The matrix for defining the three categories of TSFs is shown in Table 2.5.

Table 2.5 Hazard Rating/Height Matrix to Derive TSF Categories (modified after DME, 1999)

TSF Categories				
Hazard Rating*		High	Significant	Low
Maximum Embankment Height**	>15 m	1	1	1
	5 - 15 m	1	2	2
	< 5 m	1	2	3

*All cross-valley facilities, or facilities which block or significantly impede the flow in natural drainage lines, are to be considered as Category 1 TSF regardless of embankment height.

** In-pit TSFs are to be classified assuming an embankment height of less than 5m.

International Commission on Large Dams (ICOLD) introduces a framework for dam consequence classification that is based on potential effects to life safety, environmental values, cultural values, infrastructure, and economic conditions (Table 2.6). The framework offers some indicators for the categories, classifying the dam into one of five categories, ranging from Low to Extreme (ICOLD, 2025).

ICOLD introduces Population at Risk (PAR) and Potential Loss of Life (PLL) terms in determining life safety. The PAR in an inundation area (due to the dam breach) provides an indication of the number of individuals who could be exposed to the hazard. This includes persons who live in the inundation area, as well as those present on a short-term or intermittent basis, such as seasonal or recreational visitors and temporary travellers. PLL in the inundation area, resulting from the breach in the dam, is an assessment of potential fatalities within the PAR. This assessment is dependent on numerous factors, including the depth of flow, velocity, the time of day, the exposure time of the population (e.g., seasonal or recreational visitors, temporary travellers), the provision of advanced warning, the topography, transportation routes, and mobility.

Table 2.6 Tailings Dam Consequence Classification (ICOLD, 2025)

D _a	Incremental Losses				
Low	none	none	Minimal short-term loss of environmental values. No expected impact on livestock / fauna drinking water. Limited area of impact and restoration feasible in short term.	Minimal effects and disruption of business and livelihood. No measurable effects on human health. No disruption of heritage, recreation, community, or cultural assets.	Low economic losses: area contains limited infrastructure or services.
Significant	1-10	none	Limited loss or deterioration of environmental values. Potential contamination of livestock/fauna water supply. Moderate area of impact and restoration possible.	Limited effects and disruption of business and livelihood. No measurable effects on human health. Limited loss of regional heritage, recreation, community, or cultural assets	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes. Moderate economic loss.
High	10-100	1-10	Significant loss or deterioration of critical environmental values. Potential contamination of livestock/fauna water supply. Potential area of impact 5 km ² to 20 km ² . Restoration possible within a moderate time frame.	Many people affected by disruption of business, services, or social dislocation. Significant loss of regional heritage, recreation, community, or cultural assets. Potential for some short-term human health effects.	High economic losses affecting infrastructure, public transportation, and commercial facilities, or employment. Moderate relocation costs and/or compensation to communities.
Very High	100-1000	10-100	Major loss or deterioration of critical environmental values including rare and endangered species of high significance. Potential area of impact >20 km ² . Restoration or compensation possible but very difficult and requires a moderate to long time frame	A high number of people affected by disruption of business, services, or social dislocation for more than one year. Significant loss of national heritage, recreation, or community facilities or cultural assets. Significant long-term human health effects.	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facilities, storage facilities for dangerous substances), or employment. High relocation costs and/or compensation to communities
Extreme	>1000	>100	Catastrophic loss of critical environmental values including rare and endangered species of high significance. -Very large areas of potential impact. Restoration or compensation in kind impossible or requires a very long time.	A large number of people affected by disruption of business, services, or social dislocation for years. Significant National heritage or community facilities or cultural assets destroyed. Potential for Severe and/or long-term human health effects.	Extreme economic losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances or employment. Very high relocation costs and/or compensation to communities and very high social readjustment costs.

2.6 Risk Assessment

2.6.1 General Risk Assessment Techniques

The risk assessment is used in a wide range of sectors and disciplines. Various definitions are used to define the terminological meaning of risk. In technical disciplines, risk is often defined as the combined effect of the occurrence likelihood of an unwanted event and the magnitude of the hazard (DHI, SGI & GH, 2007). Risk, as a more standard approach, can be defined as the combination of probability and consequence of an unwanted event (RET, 2008): In general, risk assessment consists of three consecutive stages: risk identification, risk analysis, and risk evaluation.

During risk identification stage, a clear understanding of risk and the factors contributing to risk is required to identify and describe risk. The risk identification process aims to understand all the key risk events that are relevant to a project, activity, or other situational context; define their cause-and-effect relationships; identify the nature and extent of all potential consequences (for example, financial, environmental, social, economic, safety); and understand their likelihood for occurring (RET, 2008).

On the other hand, risk analysis aims to produce outputs that can be used to evaluate the nature and distribution of risk. Risk analysis techniques include qualitative, semi-quantitative, and quantitative approaches. Qualitative risk assessment techniques use descriptive terms to define the likelihoods and consequences of risk events. These methods are quick and relatively easy to use and can provide a general understanding of comparative risk between risk events. Semi-quantitative risk assessment takes the qualitative approach further by attributing values or multipliers to the likelihood and consequence groupings. Quantitative risk assessment follows the basic risk assessment approach to its full extent by attributing absolute values to hazards and consequences. Probability estimates are made regarding event frequency, while consequences are estimated using any consistent measure selected according to the

nature of the application (RET, 2008). A variety of disciplines uses different risk assessment methodologies. Some examples are given below (DHI, SGI & GH, 2007).

Human health risk assessment: The assessment of the risks to human health posed by exposure to substances released by man into the environment. The most preferred human health risk assessment model is that outlined by the National Research Council of the Academy of Sciences. Four steps of that model are:

- Hazard identification involves a qualitative assessment of the presence and degree of hazard an agent could have on potential receptors.
- A dose-response assessment further evaluates the quantitative relation between the dose and the toxic response.
- Exposure assessment estimates the magnitude of actual and/or potential receptor exposures to environmental contaminants, the frequency and duration of these exposures, the nature and size of the populations potentially at risk, and the pathways by which the risk group may be exposed.
- Risk characterization involves integrating information from the first three steps to develop a qualitative or quantitative estimate of the likelihood that any hazards associated with the agent of concern will be realized in exposed people.

Ecological risk assessment: The ecological risk assessment evaluates the probability or likelihood that adverse ecological effects will occur (or have occurred or are occurring) due to exposure to stressors from various human activities.

Engineering risk assessment: The assessment of the risks associated with the construction and the use of plants and structures, including component, material, and operator failure/error and the consequences.

Environmental risk assessment: Examining risks resulting from a system that threatens ecosystems, animals, and man.

Generally, a risk assessment attempts to answer the following fundamental questions (MAC, 2017):

- What can happen (unwanted event) and how (failure mode)?
- If it does happen, what are the consequences?
- What is the likelihood (probability) that such an unwanted event will happen?
- Can the risk be practically eliminated?
- What can be done to reduce the likelihood?
- What can be done to reduce the consequences?
- Is the level of risk tolerable or acceptable, and does it require further treatment?

As will be discussed, the tolerable risk related to dam safety considers water-retention dams and accounts only for loss of life (Bowles, 2007). The primary form of dam safety risk analysis results is a set of probability consequences or (f, N) pairs. In this analysis, f is an estimate of the probability that N fatalities occur in a particular dam failure exposure scenario. In developing an adequate risk analysis framework for a particular dam, the complete set of these pairs should be representative of the entire range of plausible dam failure exposure scenarios for the related dam comprising i) all failure modes over the entire range of initiating event conditions, and ii) all exposure conditions affecting the population at risk (regarding day or night, weekend or weekday, season of the year, time of issuance of a warning, etc.).

The terms acceptable risk and tolerable risk are not interchangeable terms, as can be examined from the following definitions:

- i. Acceptable risk is defined by the UK Health and Safety Executive (HSE) (1995) as a risk for life or work, everyone who might be impacted is prepared to accept, assuming no changes in risk control mechanisms.

- ii. ICOLD (2005) defines a tolerance risk and adapted from HSE (2001) as a risk within a range that society can live with to secure certain net benefits. It is a range of risks that we do not regard as negligible or as something we might ignore but rather as something we need to keep under review and reduce it still further if and as we can.

The four conditions in the definition of tolerable risk have very practical implications and are all familiar considerations in the dam safety field, as indicated below:

- i. To secure certain net benefits: Dams are initially constructed to provide benefits to their owners or society in general, but some are decommissioned when they no longer serve a useful purpose, or their impacts are judged to outweigh their benefits.
- ii. A range of risks that we do not regard as negligible or as something we might ignore: In most cases, dam failure risks are not considered to be negligible, except possibly for the smallest of dams in very remote locations or for such unlikely failure modes as one caused by a significant meteor impact.
- iii. Keep under review: Traditional dam safety programs include surveillance regimes, periodic inspections, and design reviews.
- iv. Reduce it still further if and as we can: Risks associated with existing dams are reduced below their design levels through structural and nonstructural measures, including improved dam safety management systems.

From studies on perceived risk, people's concerns have been grouped into two broad categories:

- i. Individual concerns: "How individuals see the risk from a particular hazard affecting them and things they value personally ... They may be willing to live with a risk that they do not regard as negligible, if it secures them or society certain benefits provided that such risks are kept low and clearly controlled" (HSE 2001).

- ii. Societal concerns: “The risks or threats from hazards which impact on society and which, if realized, could have adverse repercussions for the institutions responsible for putting in place the provisions and arrangements for protecting people...Societal concerns include multiple fatalities, exposure of especially sensitive groups, and the uneven distribution of risks and benefits. The occurrence of multiple fatalities in a single event are referred to as societal risk, which is therefore a subset of societal concerns.” (HSE 2001).

ALARP (as-low-as-reasonably-practicable) is a key consideration in satisfying the requirements for tolerability of risks. The ALARP principle is an explicit consideration under HSE (2001) and ANCOLD (2003) tolerable risk guidelines. Bowles (2007) summarizes and lists some crucial aspects of the ALARP principle as a condition for tolerable risk, cost-effectiveness, willingness to pay, gross disproportion test, existing good practice, defensibility and liability, uncertainty in risk evaluation, optioneering, future risk reduction, and incommensurable and intangible factors. Bowles (2007) also compares some tolerable risk evaluation guidelines used in dam safety. Two of them are the HSE and ANCOLD guidelines.

Both guidelines establish an individual tolerable risk limit of 1 in 10,000 per year. HSE and ANCOLD apply this threshold to the individual (or group) at the greatest risk. Risks exceeding this limit are considered unacceptable and must be reduced to at least this threshold, with further reductions required to achieve a level that is as low as reasonably practicable (ALARP). While ANCOLD applies the individual tolerable risk limit of 1 in 10,000 per year to existing dams, it applies a more strict limit of 1 in 100,000 per year for new dams or significant modifications to existing dams.

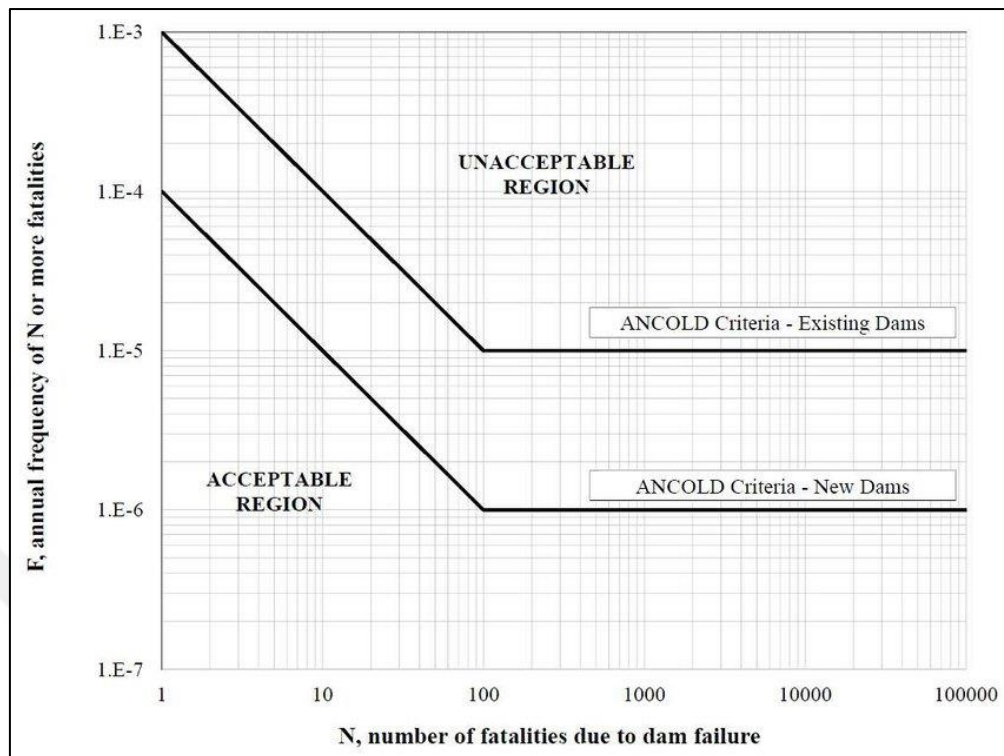


Figure 2.5: Societal Risk Acceptance for New and Existing Dams (ANCOLD; 2003)

While the individual tolerable risk guidelines share the same limit value for existing dams, the societal tolerable risk guidelines differ. HSE sets a probability of 1 in 5,000 per year or higher for 50 or more fatalities as unacceptable. Risks below this threshold are considered acceptable, subject to ALARP and disproportionality considerations. According to ANCOLD, dams with failure risks that exceed the tolerability criterion on an F-N chart of incremental life loss—shown in Figure 2.5 for existing dams and new dams or major augmentations—are considered to cause an unacceptable level of risk (Bowles, 2007).

2.6.2 Cumulative Risk Assessment

The Australian Government's Leading Practice Sustainable Development Program for the Mining Industry released a handbook addressing risk assessment and management within the Australian mining sector. The handbook recommends extending current risk assessment practices to more holistic approaches (RET, 2008).

It highlights that risk management processes in the minerals industry often focus on the incremental risks associated with the operation of individual facilities. While this approach may be appropriate for remotely located single mine operations, it becomes inadequate when mining and mineral processing activities are clustered, occur alongside other industries, or are situated near sensitive receptors. In such cases, cumulative impacts must be considered. A broader, more integrated approach is necessary to develop strategies that protect human health and the environment. This approach must account for multiple sources, pathways, and routes of exposure, potentially requiring more complex analyses, such as cumulative risk assessment. Cumulative risk can arise from the combined effects of multiple mining operations within a region or from the aggregation of various impacts from a single mine (RET, 2008).

The U.S. Environmental Protection Agency (EPA) has made the most significant contribution to cumulative risk assessment. The EPA published a document titled Framework for Cumulative Risk Assessment, which outlines the fundamental components of the cumulative risk assessment process (EPA, 2003). The EPA defines cumulative risk as the combined risks from aggregate exposures to multiple agents or stressors. The report highlights several key points derived from this definition of cumulative risk. First, cumulative risk involves multiple agents or stressors, meaning that assessments based on a single chemical or stressor do not qualify as cumulative risk assessments under this definition. Second, there is no restriction that the agents or stressors must be chemicals; they may also include biological or physical agents, or activities that, directly or indirectly, alter or result in the loss of essential elements such as habitat. Third, this definition necessitates the combination of risks from multiple agents or stressors. However, it does not imply that the risks should simply be added together; rather, an analysis must be conducted to understand how the risks from various agents or stressors interact.

An analysis, characterization, and potential quantification of the combined risks to human health or the environment from multiple agents or stressors are essential components of cumulative risk assessment. The report emphasizes that one key

aspect of this definition is that a cumulative risk assessment does not necessarily need to be quantitative, as long as it satisfies the other specified requirements. The report further underscores that the framework is conceptually similar to the approaches used in both human health and ecological assessments, yet it is distinctive in several respects, as discussed below. Figure 2.6 provides schematic representations of the various approaches to conducting risk assessments.

- Its focus on the combined effects of multiple agents or stressors differentiates it from many current assessments, where multiple stressors are typically evaluated in isolation and presented as if the others are absent.
- There is a greater emphasis on the specific populations potentially affected, rather than hypothetical receptors, as multiple stressors are impacting the same population.
- The consideration of cumulative risk may require a broader exploration of non-chemical stressors, expanding beyond the scope of traditional risk assessments.

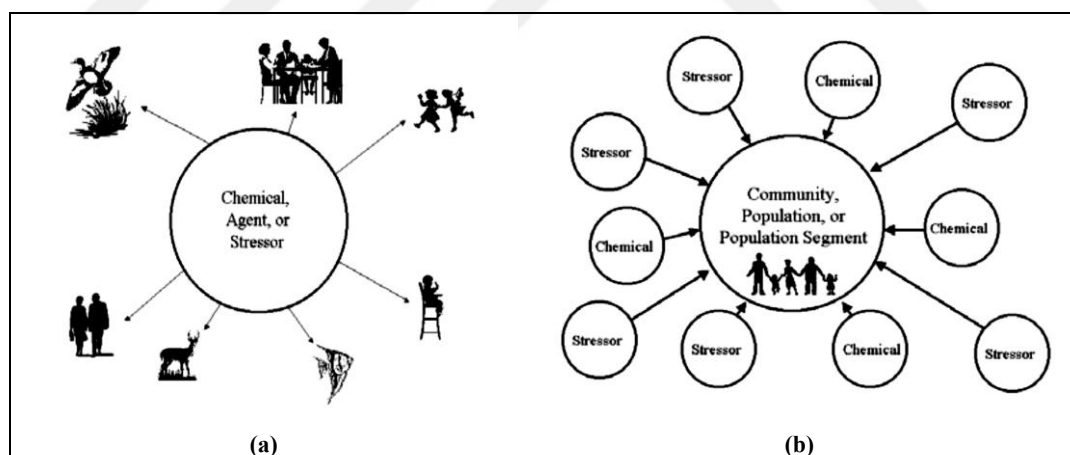


Figure 2.6: Traditional Stressor-Focused (a) and Population-Based (b) Assessments

In the presented report, the EPA provides examples of cumulative risk assessments, as well as assessments that would not be classified as cumulative risk assessments, which are outlined below. It is important to note that each example assumes the presence of a defined individual or population.

Single-Agent or Single-Stressor Assessment: Risks associated with a single agent or stressor may accumulate over time across various sources, environmental pathways, or exposure routes. This concept is defined as aggregate risk, which refers to the risk resulting from the total exposure to a single agent or stressor. While this type of assessment could be referred to as a cumulative risk assessment in some reports, within the context of this framework, such assessments are designated as aggregate risk assessments. Examples of this approach include a multisource assessment of benzene-related risks within a community or an evaluation of individual risk from a specific pesticide considering all its uses.

Multiple-Stressor Assessment: Exposures to various agents or stressors can accumulate over time, across different pathways, sources, or routes. These stressors may cause similar or diverse effects. A multiple-stressor risk assessment may focus on evaluating the risks and related health or ecological impacts of each stressor individually or it may assess the combined risk from one or more of these effects or impacts. A multiple-stressor cumulative risk assessment differs from a series of aggregate risk assessments in that it evaluates the combined impact of multiple stressors, including the potential interactions between them. An example of a multiple-stressor, single-effect cumulative risk assessment would be the assessment of the combined risk to an individual or population from a group of pesticides that act similarly and produce the same effect.

2.6.3 Risk Assessment of Tailings Dams

Risk assessment of tailings dams is an essential component of tailings management. According to the Australian National Committee on Large Dams (ANCOLD), risk assessment is applied in various forms within the scope of tailings management to evaluate specific risks associated with tailings design and operations, whether individually or in combination. The chosen assessment method depends on factors such as the complexity of the risk, the criticality of the element under consideration (e.g., safety, health, environment, business continuity), the potential consequences

of failure, and the availability of data, both in terms of quantity and quality. A comprehensive risk assessment of a tailings dam should clearly identify key indicators of potential failures, whether related to individual components or to the interaction of multiple factors that could collectively lead to a failure (ANCOLD, 2012).

In the context of tailings storage facilities, risk analysis should consider the main components of the facility which include (ICOLD, 2001):

About Dam and Foundations:

- i. Has the dam been designed by competent engineers, with due regard for foundation conditions, internal drainage, slope stability, seismic loading, and contaminant containment?
- ii. Where tailings or cycloned sand are used for construction, has the structure been assessed with the same rigour as an earth/rockfill dam?
- iii. Is the dam instrumented and/or monitored, so as to reveal any abnormal behaviour?

About Water Management Systems:

- i. Are the decant systems secure and have all pipes through the dam or foundation been adequately sealed and/or protected against piping failure?
- ii. Is there sufficient flood storage capacity?
- iii. Are spillways and/or diversions adequate for the design floods?
- iv. Are there any hazards associated with the tailing delivery lines and water reclaim lines?

About Closure:

- i. Has the structure been designed to accommodate potential changes in operating conditions over the closure period, e.g., erosion, floods, sediment inflows or natural landslides, etc.?
- ii. Are the closure works suitable to reduce the potential for contaminant transport?

2.7 Guidelines, Operating Standards and Best-Practices related to Tailings Management

Different documents address various aspects of the design, construction, operation, closure, and management of tailings facilities, including manuals, guidelines, and other regulatory frameworks. The guidance and regulation concerning tailings dam safety have evolved over time. By the mid-1960s, the recognition of geotechnical risks and the need for enhanced safety in tailings dams led to the development of regulations in British Columbia, Canada, in 1971. These regulations followed the Chilean decree of 1970, which prohibited the construction of upstream tailings dams in response to a major earthquake in March 1965, during which 11 tailings dams were either severely damaged or failed, with the most notable being the El Cobre dam (Herza et al., 2019).

In 1976, the International Commission on Large Dams (ICOLD) established a subcommittee to address safety concerns related to tailings dams, which subsequently produced a design manual in 1982 and several technical bulletins. In both Canada and Australia, dam safety is primarily legislated at the provincial or state level, with legislation often referencing guidelines established by the Canadian Dam Association (CDA) and the Australian National Committee on Large Dams (ANCOLD) for technical requirements. In addition, certain states (e.g., New South Wales and Western Australia in Australia) and mining companies (e.g., Rio Tinto) have developed their own tailings dam safety guidelines (Herza et al., 2019).

Guidance on tailings dam safety continues to be updated by organizations such as CDA, ANCOLD, the Mining Association of Canada (MAC), the International Council on Mining and Metals (ICMM), and ICOLD, along with other national and international bodies. MAC published “A Guide to the Management of Tailings Facilities”, with the first edition released in 1998 (MAC, 1998). This guide was among the first and most comprehensive resources specifically focused on tailings management in the mining industry.

ANCOLD provides a comprehensive set of guidelines to ensure the safe design, operation, and maintenance of dam structures. These guidelines outline best practices for water and tailings dams in Australia and encompass various aspects of dam engineering and management. Specifically, ANCOLD's guidelines include risk assessment processes, geotechnical investigations, design specifications and recommendations, instrumentation and monitoring systems, consequence classifications, and dam safety management protocols (ANCOLD, 2012).

In August 2020, ICMM published the Global Industry Standard on Tailings Management, developed in collaboration with the UN Environment Programme and the UN Principles for Responsible Investment (PRI). The primary objective of this standard is to achieve *zero harm to people and the environment, with zero tolerance for human fatality* in the operation of mine tailings facilities. It is regarded as the new industry benchmark for governance structures required to safely manage tailings storage facilities. Furthermore, the standard sets the engineering criteria for tailings facility design at the highest levels, surpassing other existing standards in terms of safety and technical rigor.

2.8 Review of Previous Literature on Advancements in Risk Assessment for Tailings Dams

There are plenty of previous research in the literature to improve risk assessment of tailings dams. Accordingly, Mara et al. (2007) developed a methodology to evaluate the hazards associated with mine waste tailings dams, which involves quantifying hazardous components and assigning a hazard value through a system of criteria, indexes, and ratings. The hazard associated with a dam is quantified using the RB index, defined as in Equation 2.1.

$$RB = \frac{CA}{\alpha \times BA + \beta \times CB} \quad (2.1)$$

where the equation parameters are obtained as discussed below.

The BA index is determined by the characteristics of the dam or deposit, including its dimensions, type, discharge, and importance class, as well as its location, considering factors such as ground conditions and seismicity, and the condition of the lake or waste deposit. The CB index is influenced by the dam's current state, the complexity of its operational controls and monitoring systems, the level of maintenance, the dam's performance over time, the condition of the accumulation lake, and the extent of site-specific knowledge available. The CA index quantifies the potential consequences of damage to the dam or deposit, taking into account factors such as the risk of loss of life, environmental impacts, and potential socio-economic effects. Depending on the value of the RB index, the dams are assigned to one of four hazard categories given in Table 2.7.

Table 2.7 RB Index and Associated Hazard Categories (Mara et al. 2007)

Hazard Category	Index Value	Note
A	$RB > 0.8$	a dam of exceptional importance
B	$0.8 \geq RB > 0.15$	a dam of special importance
C	$0.15 \geq RB > 0.05$	a dam of normal importance
D	$RB \leq 0.05$	a dam of low importance

Mara et al. (2007) defined the risk of tailing dams to surface waters as given in Equation 2.2.

$$\text{Risk} = \text{RB} \times \text{WRI} \quad (2.2)$$

where the Water Risk Index (WRI) quantifies the environmental vulnerability to pollution resulting from potential accidents at the tailings dams. The WRI value is calculated as the base-10 logarithm of the summed equivalent values of the Water Risk Classes (WRC). Thus, the risk caused by tailings dams to surface waters is determined by Equation 2.3:

$$\text{Risk} = \left[\frac{\text{CA}}{\alpha \times \text{BA} + \beta \times \text{CB}} \right] \times \log(\Sigma \text{WRC}) \quad (2.3)$$

Silva et al. (2008) identified three widely accepted methods for estimating event probabilities: (1) using historical data and the frequency of observations, (2) deriving probabilities through probability theory (mathematical modeling), and (3) quantifying expert judgment (subjective probabilities). A semi-empirical relationship between the factor of safety and the annual probability of failure was proposed, based on the quantification of expert judgment. A case study of a tailings dam demonstrated that risk assessment grounded in expert judgment quantification offers a systematic framework for making informed management and engineering decisions regarding dam safety and other geotechnical issues. A graph illustrating the relationship between the factor of safety and the annual probability of failure was constructed. Figure 2.7 classifies earth structures into four categories based on the quality of engineering practices, ranging from the best (Category I) to the poorest (Category IV). The study determines the engineering level by evaluating practices related to design, investigation, testing, analysis and documentation, construction, and operation and monitoring. The four categories correspond to the following types of facilities:

- **Category I:** Facilities designed, constructed, and operated using state-of-the-art engineering practices. These facilities typically have high potential failure consequences.
- **Category II:** Facilities designed, constructed, and operated according to standard engineering practices. This category includes many conventional facilities.
- **Category III:** Facilities lacking site-specific design and exhibiting substandard construction or operation. Temporary facilities and those with low failure consequences are often classified in this category.
- **Category IV:** Facilities with minimal or no engineering design.

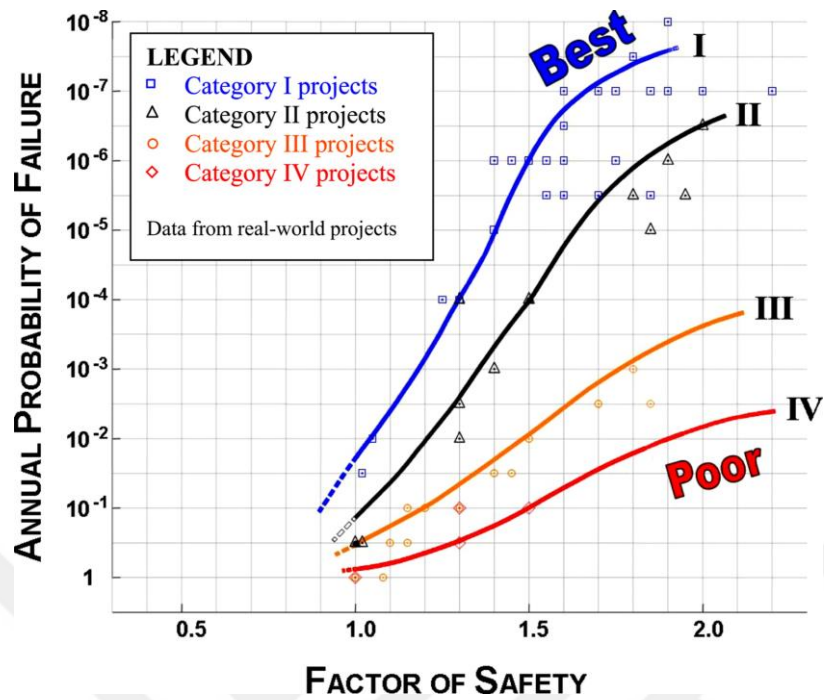


Figure 2.7: Factor of safety versus annual probability of failure (Silva et al. 2008)

Xin et al. (2011) conducted an analysis of tailings dam accidents worldwide and developed an evaluation index system for assessing the stability of tailings dams (Table 2.8). The set pair analysis method was employed to evaluate the probability of tailings dam failure. The results of this assessment are presented in (Table 2.9).

Table 2.8 Tailings Dam Stability Assessment Index System

1 level index	2 level index	3 level index
Tailings dam stability assessment	Geological factors B_1	Tailings properties C_1 Geological features C_2
	Engineering factor B_2	Deposited beach length C_3 The starter dam downstream slope C_4 Leakage facilities C_5 Types of Tailings dam C_6 Tailings dam height C_7 Drainage facilities C_8 Groundwater condition C_9 Earthquake intensity C_{10}
	Daily maintenance and environmental factors B_3	Safety management C_{11} Dam protection C_{12} Dam safety monitoring C_{13}

Table 2.9 Tailings Dam Break Probability

Parameter		Definitions		
Grade	Tailings dam breaks at any time	Safety facilities exist serious hidden trouble, if not timely treatment will lead to tailings dam break	Tailings dam meet the basic conditions for safe production	Tailings dam fully equipped with the conditions for safe production
Connection number	$-1 \leq \mu < -0.5$	$-0.5 \leq \mu < 0$	$0 \leq \mu < 0.5$	$0.5 \leq \mu \leq 1$
Quantitative evaluation	4	3	2	1

The routing and movement of tailings flow downstream following a tailings dam failure are simulated using the DAMBRK model, and the distribution of individuals and structures within the affected area is analysed. A comprehensive weighted factor method is employed to construct a consequence evaluation model. This model accounts for factors such as the tailings dam scale, loss of life, economic losses, and social and environmental impacts. Equation 2.4 is used to evaluate the consequences (C) of a tailings dam failure:

$$C = W_1D + W_2H + W_3P + W_4S \quad (2.4)$$

where D, H, P, and S represent the tailings dam scale, loss of life, economic losses, and social and environmental impact, respectively. W_i values are the corresponding weight factors. The severity classification is provided in Table 2.10. The risk assessment of the tailings dam is ultimately presented in matrix form as an integrated risk classification, as shown in Table 2.11 (Xin et al., 2011).

Table 2.10 Dam Break Severity Classification

Dam break severity	Light effect	Moderate effect	Height effect	Extreme effect
c range	$1 \leq c < 1.75$	$1.75 \leq c < 2.5$	$2.5 \leq c < 3.25$	$3.25 \leq c \leq 4$
Quantitative evaluation	1	2	3	4

Table 2.11 Tailings Dam Integrated Risk Classification

Tailings dam integrated risk classification		Dam break severity classification			
		Extreme effect (4)	Height effect (3)	Moderate effect (2)	Light effect (1)
Tailings dam break probability	tailings dam break at any time (4)	16	12	8	4
	Safety facilities exist serious hidden trouble, if not timely treatment will lead to tailings dam break (3)	12	9	6	3
	Tailings dam meet the basic conditions for safe production (2)	8	6	4	2
	Tailings dam fully equipped with the conditions for safe production (1)	4	3	2	1

Mara et al. (2011) assessed the vulnerability of tailings dams to NATECH (Natural Hazards Triggering Technological Disasters) events and proposed both structural and non-structural measures to mitigate potential casualties and damage resulting from the failure of these hydrotechnical structures. NATECH risk values were calculated by averaging hazard coefficients for various natural hazards, based on a matrix evaluation approach (Equation 2.5).

$$K(m) = \sqrt{\frac{K(a) \times K(b)}{6}} \times [K(c) + K(d) + K(e) + K(f) + K(g) + K(h)] \quad (2.5)$$

Using the NATECH failure consequences Index (FC) proposed for tailing dams (Table 2.12) the risk of a tailings dam is determined by multiplying the failure index with the consequence index.

Table 2.12 Failure Consequence Index (FC)

Partial Criteria	Parameters and Indices			
1 population density in the downstream area	more than 20,000 inhabitants	300 to 20,000 inhabitants	scarcely populated	no population
	20	10	5	0
2 warning and alarm system	none	alarm system for local authorities	alarm system not tested or adapted by civil defence authorities	alarm system in place and tested by civil defence authorities
	20	10	5	0
3 Hazardous potential of the tailing dam waste material	mining tailing dam with dangerous toxic substances	Mining tailing dam with hazardous substances	Mining tailing dam with large quantity of inert sterile waste	only mining tailing dam
	20	10	5	2
4 economical entities in downstream area	industries with more than 100 employees	small industries	private workshops	no industrial activity
	10	5	3	0
5 land use around dam	agriculture	forests or pastures	uncultivated, barren	
	10	5	0	
6 environmental impact of potential failure	ecological disaster	significant effects	negligible effects	
	5	3	1	
7 effects of potential failure on river basin	failure of downstream cascade	jeopardising of flood control	no effects on flood control	
	15	7	2	

Mei (2011) conducted a quantitative assessment of dam failure risks in tailings dams using the weakness theory. The study involved calculating the probability of dam failure (P_f) by treating volume weight, internal friction angle, and cohesion as random variables, and applying the Monte Carlo model. A flow model was developed to simulate the movement of tailings post-failure, incorporating hydrological, hydrodynamic, and non-Newtonian fluid dynamics theories, in order to estimate the submergence range resulting from dam failure. The loss ratio due to dam failure was computed by evaluating the loss of life, financial costs, and environmental impact. The loss level (V) of the submergence range was determined using a multi-stress weighted method as shown in Equation 2.6.

$$V = W_1H + W_2P_E + W_3S \quad (2.6)$$

where H , P , S is loss of life, economic loss and influences on social environment, respectively, and W_1 , W_2 , and W_3 are the corresponding weights derived through expert evaluation and the analytic hierarchy process (AHP). The risk of dam failure in tailings dams was quantified by the weakness level, defined as $R = P_f \times V$.

Pan and Dong (2012) proposed a risk evaluation index system for tailings ponds based on Fuzzy Sets Theory, an effective tool for addressing subjective judgment. The proposed methodology integrates the knowledge and expertise of multiple specialists. The index weights are determined by two primary risk factors: risk probability and risk impact. To address issues of subjectivity and uncertainty in determining both index weights and values, the triangular fuzzy theory is employed. It is emphasized that the most significant distinction between their approach and other fuzzy risk assessment methods is the use of an algorithm to resolve inconsistencies within the fuzzy preference relations.

Salgueiro et al. (2008) presents a statistical approach for preliminary risk evaluation of breakage in tailings dam. The method relies on a historical database containing two sets of qualitative data. The first set includes variables observable prior to a disaster (e.g. dam type, size, location, and operational status), while the second set is related to the consequences of the disaster (e.g. failure type, sludge characteristics, fatality categories, and the downstream extent of damage). The method employs a modified form of correspondence analysis, in which the second set of attributes is projected as supplementary variables. A qualitative regression is then performed, relating the predicted variables (from the second set) to the predictor variables (from the first set). Based on the derived relationship, the risk of dam failure in a new case can be assessed using the observable variables. The resulting risk rankings were validated through expert knowledge.

Song et al. (2022) developed an evaluation index system and corresponding grading standards for tailings dam failure. Both subjective and objective aspects of the evaluation indices were addressed by integrating matter-element extension theory with game theory. The risk evaluation indicators for tailings dam failure were

categorized into five main areas and 14 sub-items. The categories include seepage failure, dam instability, structural damage, flood overtopping, and safety management. The methodology incorporates a level variable eigenvalue, referred to as the evolution of value, which not only enables precise determination of the tailings dam's risk grade but also allows for the identification of the risk level's evolutionary trajectory. Based on China's safety standards, regulations, and specifications for tailings ponds, the results indicate that the tailings dam failure is classified as Grade I, representing a normal (low-risk) tailings reservoir, with an eigenvalue of 1.3. This suggests an evolutionary trend toward a Level II dam failure (higher-risk).

Hao et al. (2022) developed a causal coupling hierarchical structure model to analyse the disaster-causing factors of tailings dams, employing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Interpretive Structural Modelling (ISM) methodologies (Figure 2.8). Causal relationships among the disaster-causing factors were analyzed, identifying the key factors and their overall impact. Based on the hierarchical structure model, the Pythagorean fuzzy analytic hierarchy process was applied to calculate the hierarchical weights of the factors. Additionally, DEMATEL and complex network analysis were used to determine the centrality and clustering coefficient of each disaster-causing factor. A model for determining the weights of these factors was proposed, incorporating centrality (α), hierarchical weight (β), and clustering coefficient (θ) as core components. By integrating the cloud model and matter-element extension model, a comprehensive weight model was proposed as a risk assessment tool for tailings dam failure. Additionally, an expert consultation method was employed to determine the correlations among 36 factors and to establish the connections between disaster-causing factors, ranging from secondary to primary factors. Questionnaires were distributed to professors, associate professors, and tailings dam safety managers. The model results indicate that the direct causes of tailings dam failures include flood discharge capacity, dam deformation, phreatic line depth, outer slope ratio of the tailings embankment, and the site selection of the tailings dam. The underlying causes are related to the safety management system, regulations, and capital investment.

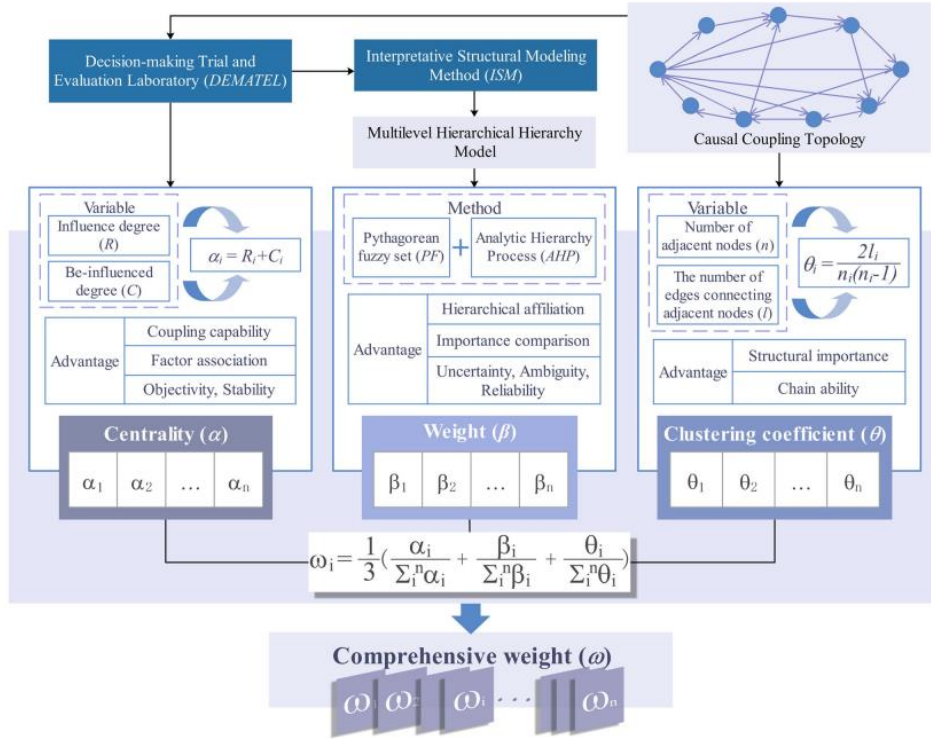


Figure 2.8: Model for determining the comprehensive weight (Hao et. al. 2022)

Zheng et al. (2022) proposed a method combining DEMATEL and MISM to analyse the evolution of tailings dam failure risk. 35 risk factors influencing tailings pond failure were identified, and an index system was developed to evaluate the factors contributing to dam failure across four dimensions: personnel, management, environment, and system. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) was employed to analyse the influence relationships among these factors, identifying the key causal elements. Subsequently, the Modified Interpretative Structural Model Method (MISM) was used to classify the causal factors into five levels of influence and to assess the degree of integrated influence between the risk factors. Based on these analyses, an evolutionary model of tailings pond dam failure risk was constructed. It was reported that system-related risks accounted for 58.58% of the total weight, personnel risks accounted for 15.51%, management risks for 20.07%, and environmental risks for 5.84%. The study revealed that rainfall intensity was a critical causal factor, while the dam height and depth of the seepage line constituted significant causal elements. In the risk evolution

model, 30 factors exhibited high mutability and correlation, playing a transitional role in risk transfer.

Zhen et al. (2022) identified hazards and their interrelationships to construct a propagation network of tailings dam failure risk (PNTDFR) based on complex network theory. Recognizing the multi-stage nature of failure risk propagation, a multi-stage collaborative hazard remediation method (MCHRM) was proposed to assess the importance of hazard nodes. This method integrates various centrality approaches under different hazard remediation (deletion) ratios to identify the critical hazards leading to tailings dam failure. Applying this methodology to Feijão Dam I, 30 key hazards were identified in the trigger state during the failure formation process of the dam.

Chovan et al. (2021) present a risk assessment tool specifically developed for Tailings Storage Facility (TSF) management, building upon the work of Silva et al. (2008), which links the annual probability of failure to the factor of safety and the level of engineering. They modified this relationship to better reflect the specific characteristics of TSF cases. The annual probability of failure was integrated with a consequence rating to provide a rational and quantifiable risk evaluation (Figure 2.9). The risk assessment tool offers detailed insights into the practice level of a structure, the corresponding annual probability of failure, and the associated risk.

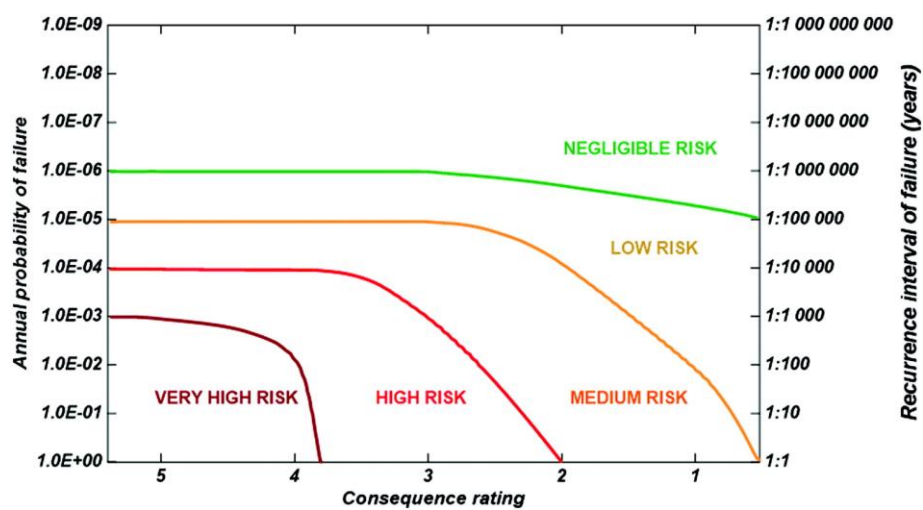


Figure 2.9: Example Risk Classifications Chart (Chovan et al., 2021)

Chen et al. (2023) developed a three-dimensional risk matrix to assess the risk of Tailings Storage Facility (TSF) failure, incorporating failure probability, event intensity, and exposure of failure-bearing bodies (Figure 2.10). Initially, the probability level is determined using uncertainty measurement theory and the extension analytic hierarchy process, based on the established assessment indicator system. The event intensity level is defined by two parameters: the volume of released tailings and the maximum distance travelled by the tailings. The exposure level is characterized by the potential loss to four failure-bearing bodies: population, economy, environment, and society. Finally, the risk index is computed using the Euclidean distance method, which is used to determine the overall risk level. The proposed model classifies the probability, intensity, exposure, and risk of TSF failure into four levels (Level I, Level II, Level III, Level IV), ranging from high to low.

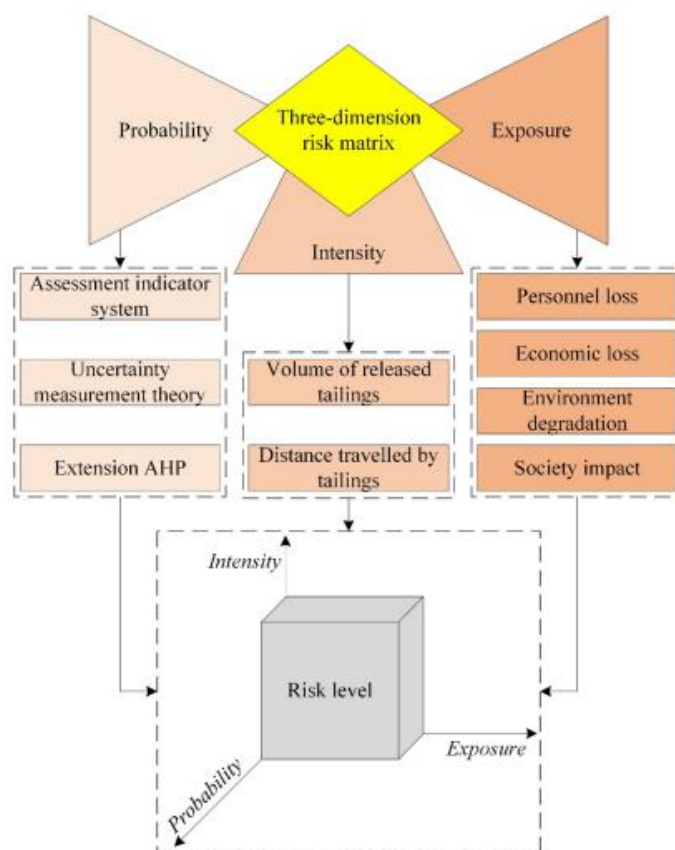


Figure 2.10: Three Dimension Risk Matrix for TSF Failure (Chen et al., 2023)

2.9 Study Motivation

Based on a review of existing literature on tailings dam risk assessment, the research gaps identified in previous studies are summarized in Table 2.13. As shown in the table, most studies focus on the risks associated with individual tailings dams, rather than considering multiple dams within the watershed, a scenario commonly observed at mining sites. Additionally, the literature review indicates that the combined risk resulting from the failure of multiple tailings dams affecting downstream a community has not been adequately addressed. Furthermore, many studies fail to cover the complete source-transport-receptor chain of risk. Literature review also reveals that even in risk assessment processes of single tailings dams social impacts, ecosystem services provided by affected environment, adverse health effects, management factors in failure of a tailings dam are not sufficiently concerned. Additionally reviewed literature is lacking the integration of dynamic, in other words time-dependent, variables to the risk assessment of tailings dams.

Table 2.13 Comparison with the Related Literature

Study	Component of Risk Assessment			Study Content		# of Dams Concerned		Combined Risk	Dynamic
	Failure Model	Transport Model	Consequence Model	New Method	Case Study	Single	Multiple		
Mara et al. (2007)	●	○	●	●	○	○	○	○	○
Salgueiro et al. (2008)	●	○	●	●	●	○	●	○	○
Mara et al. (2011)	●	●	●	●	○	○	○	○	○
Xin et al. (2011)	●	●	●	●	●	●	○	○	○
Mei (2011)	●	●	●	●	●	●	○	○	○
Pan et al. (2012)	●	○	○	●	●	●	○	○	○
Shu et al. (2012)	○	●	●	●	○	○	○	○	○
Mei et al. (2012)	●	●	●	●	○	○	○	○	○
Espósito et al. (2013)	●	●	●	○	●	○	●	○	○
Zheng et al. (2016)	●	●	○	●	●	●	○	○	○
Chovan et al. (2021)	●	●	●	●	●	●	○	○	○
Chen et al. (2022)	●	○	○	●	○	○	○	○	○
Chen et al. (2023)	●	●	●	●	●	●	○	○	○
Song et al. (2022)	●	○	○	●	●	●	○	○	○
Zheng et al. (2022)	●	○	○	●	○	○	○	○	○
Hao et al. (2023)	●	○	○	●	●	●	○	○	○
Current Study	●	●	●	●	●	●	●	●	●

CHAPTER 3

DEVELOPMENT OF THE RISK ASSESSMENT MODEL FOR A TAILINGS DAM

3.1 Introduction

The current section will conduct a detailed discussion on the fundamental factors of the conceptual risk assessment model of tailings dams developed under the scope of the current study. This conceptual model will facilitate the construction of a system dynamics model to be introduced in Chapter 4, for the time-based evaluation of risk levels associated with tailings dams, regarding the complex and dynamic interactions between the failure potential model and the consequence model considering human health, social and economic life, and environment. Accordingly, Chapter 3.2 will first address model selection criteria inline with dam status. Chapter 3.3 will outline the methodology for determining the extent of risk body of a tailings dam failure using a flow model. Chapter 3.4 provides the details of expert survey and its evaluation technique. Chapter 3.5 will outline the key aspects of the consequences of a tailings dam failure, while Chapter 3.6 will discuss the approach for estimating failure potential.

3.2 Model Selection According to Dam Status

Tailings dams are unique and highly complex structures. Their failure can have catastrophic environmental, social, and economic consequences. Therefore, robust risk assessment is paramount throughout their lifecycle.

Static and dynamic risk assessment models are two distinct approaches to managing the complex risks associated with tailings dams. The static risk assessment model for tailings dams has been developed to provide an estimation of the risk at a given moment in time. It assesses risk based on current conditions and existing data without explicitly incorporating the evolution of risk factors over time. The parameters used in the assessment (e.g., material properties, dam geometry, hydrological conditions, surrounding environment, exposed population, etc.) are typically assumed to be constant or are based on their current measured values. On the other hand, the dynamic risk assessment model for tailings dams is an approach that continuously monitors and updates the risk profile over time, accounting for changes in the dam, its environment, and operational factors. It explicitly considers how risk factors and their interactions change over the dam's lifecycle, from construction and operation to closure and post-closure.

Risk assessment of a tailings dam in this study is modelled as a dynamic or static model by dividing its lifecycle in two main stages:

- i. Active life: Deposition continues in the tailings dam hence potential amount of runout material is increasing. This situation necessitates a dynamic model, since inundation area and dependently the resultant consequence downstream changes in time.
- ii. Inactive life: This period refers to the period following closure (post-closure) or, in the case of abandonment, the post-deposition phase. Since the deposition in tailing dam is ceased, a static model is utilised to model the risk, assuming that conditions within the risk body remains unchanged.

Throughout this study tailings dams are categorised and assessed under three distinctive dam statuses according to stages of their lifecycle. Tailings dams in their active life are referred as “Active Dam”. On the other hand, tailings dams in their inactive lifetime are assessed according to their closure phase. If a tailings dam has a certain closure phase during its lifetime, it is denoted as “Closed Dam”. Tailings dams without or unknown closure phase are denoted as “Abandoned Dam”.

3.3 Risk Body and Affected Area

3.3.1 Identification of Risk Body and Its Borders

The risk assessment model will focus on the community potentially affected by a tailings dam failure, located downstream. The downstream community may be a village, a residential area or groups of them. The size or scale of the community depends on the user's choice.

The concerned community, along with its socio-economic entities and surrounding environment, is classified as a risk body. The boundaries of this risk body also define the extent of the potential consequences in the event of a failure. The impacts outside the identified risk body are not included in the risk assessment model.

3.3.2 Determination of the Extent of Affected Area Using a Flow Model

Several numerical models, such as DAN3D, MADflow, FLO-2D, and FLOW-3D, are available for simulating flooded downstream areas resulting from a tailings dam failure. Ghahramani et al. (2022) conducted a back-analysis of two well-documented historical tailings dam breaches using these models (Figure 3.1). The study demonstrated that all four models could reproduce the general behaviour of the real events. A sensitivity analysis revealed that each model is sensitive to different input parameters, although the total released volume consistently emerged as a key high-influence parameter across all scenarios.

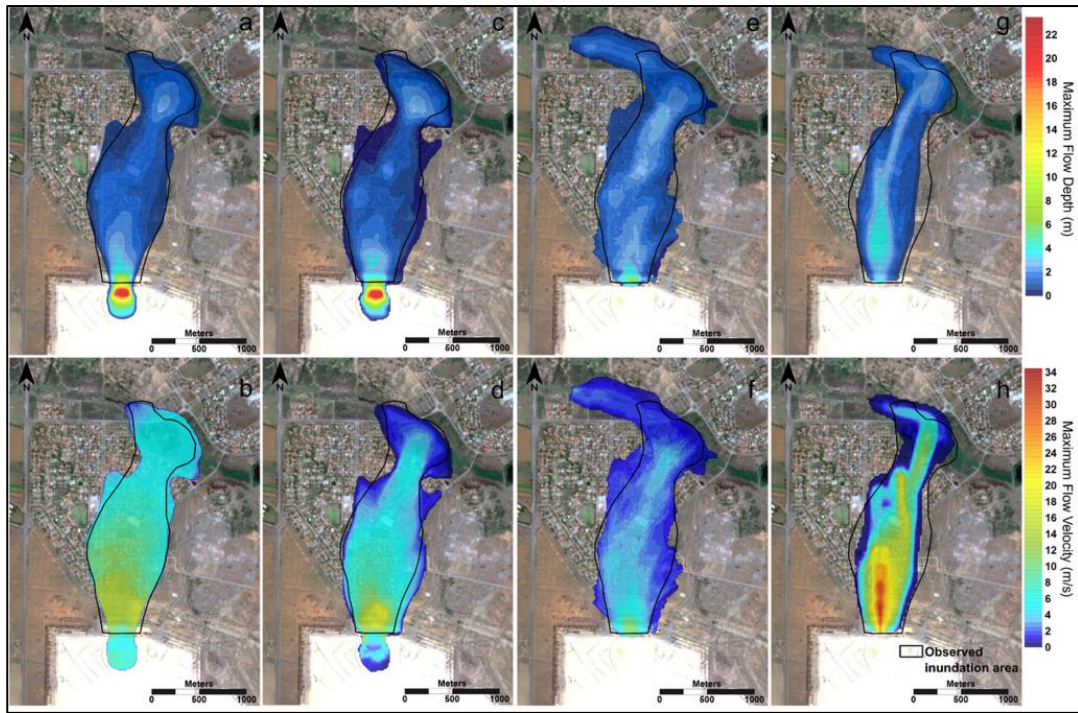


Figure 3.1: Maximum Flow Depth and Velocity Contours obtained from Different Modeling Tools for Merriespruit Tailings Flow (Ghahramani et al., 2022)

Raman and Liu (2019) employed HEC-RAS, developed by the US Army Corps of Engineers, to model the mudflow resulting from the Brumadinho tailings dam collapse. Their findings indicated that the extent of the simulated mudflow aligned with the actual flooding observed following the dam break, suggesting that this simulation technique could be applied to future dam collapse predictions.

Scholtz and Chetty (2021) compared HEC-RAS and FLO-2D as tools for analysing tailings dam breaches. The study concluded that both models are suitable for breach analysis and produce similar results, which would likely lead to comparable consequence classifications for the dam failure.

Recent advancements in Geographic Information System (GIS) technology have further facilitated dam-break simulations by integrating topographical data through software such as HEC-RAS and Google Earth. Elevation data, a primary input for flow models, is readily available through the NASA SRTM elevation dataset for most countries, often at no cost.

3.4 An Expert Survey for Evaluation of the Consequence and Failure Potential Model Parameters

This thesis study employs an expert survey to assess the scope and prioritization of parameters influencing both the failure consequences and failure potential of tailings storage facilities (TSFs). As it will detailed in Sections 3.5 and 3.6, the parameters associated with the TSF failure consequences model are classified into three categories: human health, social and economic life, and environment. Conversely, the TSF failure potential parameters are categorized according to three distinct phases of the dam lifecycle: active dam, closed dam, and abandoned dam.

Among the consequence model categories, only questions related to human health, and social and economic life were presented to the participants. The environmental section was excluded, as the prioritization of environmental parameters is considered to be similar. Additionally, judgments concerning environmental consequences may exhibit significant variation depending on location. As such, the study does not request participants to revise the priority assigned to any environmental factors.

The surveys addressing the consequence model parameters (human health, and social and economic life) and failure potential (active dam, closed dam, and abandoned dam) were managed separately with two different expert groups. This distinction was made to ensure that participants, whose professional experience and skill sets vary, could offer appropriate judgments regarding both the failure consequences and the failure potential of TSFs. Accordingly, a total of twelve experts participated in the failure potential survey, while seven experts participated in the failure consequences survey. These experts had diverse professional titles, varying levels of experience, and different educational backgrounds. The survey responses were evaluated based on the weighting of each participant's input, with the scores being accumulated collectively. Therefore, prior to having their expert opinions on specific questions, background information about each participant was collected.

3.4.1 Preparation of the Questionnaire

The parameters assessed under the question subsets of the Failure Potential Survey are presented in Table 3.1. The failure potential of Tailings Storage Facilities (TSFs) is evaluated based on failure modes capable of triggering failure, as well as management factors that are effective in mitigating or preventing such failures. This evaluation is conducted across three distinct phases of a TSF: active, closed, and abandoned.

Table 3.1 Parameters Evaluated in the TSF Failure Potential Survey

Question Sets	Parameters	Sub-Parameters	Question Code
Background	-	-	Q1
Active Dam Failure Modes	Overtopping	Extreme hydraulic events	Q.2.1
		Natural hazards	Q.2.2
		Excess water storage	Q.2.3
		Flood control facilities	Q.2.4
		Dam type	Q.2.5
	Slope Instability	Seismicity	Q.3.1
		Construction material	Q.3.2
		Seepage control	Q.3.3
		Drainage facilities	Q.3.4
		Phreatic surface	Q.3.5
		Height and inclination	Q.3.6
		Erosion	Q.3.7
		Dam Type	Q.3.8
	Internal Erosion	Seepage control	Q.4.1
		Construction material	Q.4.2
		Phreatic surface	Q.4.3
		Dry beach location and width	Q.4.4
	Foundation Failure	Dam Type	Q.4.5
		Seepage control	Q.5.1
		Drainage facilities	Q.5.2
		Foundation properties	Q.5.3
		Groundwater condition	Q.5.4
		Seismicity	Q.5.5
		Subsidence	Q.5.6
		Dam Type	Q.5.7
Active Dam Management	Dam Safety Management	Dam safety monitoring	Q.6.1
		Warning system	Q.6.2
		Emergency planning	Q.6.3
		Training and safety culture of workers	Q.6.4
		Supervision and responsibility	Q.6.5
	Internal Management	Design and construction	Q.7.1
		Qualification and Experience	Q.7.2
		Maintenance practices	Q.7.3
	External Management	External Audit	Q.8.1
		External monitoring	Q.8.2
		Regulatory control	Q.8.3
Active Dam Failure - General Evaluations	-	Effect of Failure Modes	Q.9.1
		Importance of Management Factors	Q.9.2
		Effect of Management Factors on Failure Prevention	Q.9.3

Table 3.1 Parameters Evaluated in the TSF Failure Potential Survey (cont'd)

Question Sets	Parameters	Sub-Parameters	Question Code
Closed Dam Failure Modes	Overtopping	Extreme hydraulic events	Q.10.1
		Natural hazards	Q.10.2
		Flood control facilities	Q.10.3
	Slope Instability	Seismicity design	Q.11.1
		Construction material	Q.11.2
		Seepage and drainage measures	Q.11.3
		Height and inclination	Q.11.4
		Erosion measures	Q.11.5
		Dam Type	Q.11.6
	Internal Erosion	Seepage and drainage measures	Q.12.1
		Construction material	Q.12.2
		Phreatic surface control	Q.12.3
		Dam Type	Q.12.4
	Foundation Failure	Seepage measures	Q.13.1
		Foundation properties	Q.13.2
		Groundwater condition	Q.13.3
		Seismicity measure	Q.13.4
		Subsidence measure	Q.13.5
		Dam Type	Q.13.6
Post Closure Management	-	Supervision	Q.14.1
		Monitoring and warning system	Q.14.2
		Regulatory control at closure	Q.14.3
		Closure planning	Q.14.4
		Capital investment	Q.14.5
Closed Dam Failure - General Evaluations	-	Effect of Failure Modes	Q.15.1
		Effect of Management Factors on Failure Prevention	Q.15.2
Abandoned Dam Failure Modes	Overtopping	Extreme hydraulic events	Q.16.1
		Natural hazards	Q.16.2
		Flood control measures	Q.16.3
	Slope Instability	Seismicity design	Q.17.1
		Construction material	Q.17.2
		Seepage and drainage measures	Q.17.3
		Height and inclination	Q.17.4
		Erosion measures	Q.17.5
		Dam Type	Q.17.6
	Internal Erosion	Seepage and drainage measures	Q.18.1
		Construction material	Q.18.2
		Phreatic surface control measures	Q.18.3
		Dam Type	Q.18.4
	Foundation Failure	Seepage measures	Q.19.1
		Foundation properties	Q.19.2
		Groundwater condition	Q.19.3
		Seismicity measure	Q.19.4
		Subsidence measure	Q.19.5
		Dam Type	Q.19.6
Abandoned Dam Management	-	Monitoring and warning system	Q.20.1
		Regulatory control	Q.20.2
		Dam behavior	Q.20.3
Abandoned Dam Failure - General Evaluations	-	Effect of Failure Modes	Q.21.1
		Effect of Management Factors on Failure Prevention	Q.21.2

In Table 3.1, a five-level linguistic scale comprising very high, high, moderate, low, and very low is used for the responses to all questions, except for the Background Information and the General Evaluation question sets (QS.9, QS.15, and QS.21), which are interpreted using percentile value.

Additionally, the parameters assessed in the Consequences Survey are presented in Table 3.2. As discussed earlier, the consequences of TSF failure for downstream communities will be addressed in Section 3.5, with consideration given to human health, socio-economic impacts, and environmental effects. However, due to the variability of environmental factors across different locations and to avoid underrepresenting the significance of any specific environmental aspect, the survey focused exclusively on human health and socio-economic impacts. Similar to the Failure Potential Survey, a five-level linguistic scale will be utilized to answer the questions.

Table 3.2 Parameters Evaluated in the TSF Failure Consequences Survey

Question Sets	Parameters	Sub-Parameters	Question Code
Background	-	-	Q1
Human Health	Severity	Toxicity	Q.2.1
		Damage to infrastructure and facilities	Q.2.2
		Resilience of residences	Q.2.3
		Quickness of rescue services	Q.2.4
		Vulnerability of the region to natural hazards	Q.2.5
	Degree of Preparedness	Emergency planning	Q.3.1
		First aid opportunities	Q.3.2
		Early warning	Q.3.3
		Training	Q.3.4
	Social and Economic Life	Vulnerability	Dependency on Mining
Diversity of Economic Activities			Q.4.2
Proportion of Vulnerable Groups			Q.4.3
Existence of Indigenous People			Q.4.4
Social Disturbance		Unrest	Q.5.1
		Displacement	Q.5.2
		Poverty	Q.5.3
Economic Support		Compensation	Q.6.1
		Insurance	Q.6.2
		Donation	Q.6.3

The background section aims to collect information about the professional positions, experiences, educational levels and ages of the participants. Following the background section, participants are presented with specific questions related to the parameters outlined in the Consequences and Failure Potential Survey (Table 3.1 and Table 3.2). As an illustrative example, Table 3.3 presents the set of questions related

to Overtopping and Slope Instability under the Active Dam Failure Modes category (Q.2.1 to Q.2.5 and Q.3.1. to Q.3.8) from the Failure Potential Survey. The complete set of survey questions is provided in Appendix A and Appendix B for the Failure Potential and Consequences Surveys, respectively.

Table 3.3 A Sample Part of the Questionnaire in the Failure Potential Survey

QS	Code	Parameter	Question
Overtopping	Q.2.1	Extreme hydraulic events	Extreme hydraulic (meteorological) events such as tropical rainfall, heavy snowmelt or hurricanes in the area where the tailings dam is built are expected to have an impact on tailings dam overtopping. Accordingly, to what extent does extreme hydraulic events affect the overtopping of a tailings dam?
	Q.2.2	Natural hazards	Natural disasters such as landslides, avalanches or strong winds (cyclones) in the area where the tailings dam is built are expected to have an impact on the overtopping of the tailings dam. To what extent does natural disasters affect the overtopping of a tailings dam?
	Q.2.3	Excess water storage	In the design and operation of a tailings dam, it is expected that reserving a storage volume in the reservoir for excess water that may be filled by rainfall and/or catchment runoff will have an impact on tailings dam overtopping. To what extent does reserving an excess storage volume affect the overtopping of a tailings dam?
	Q.2.4	Flood control facilities	The construction of flood control structures, such as diversion channels for flows from the catchment of the tailings dam, or weir structures to discharge flood waters from the reservoir, are expected to affect the overtopping of the tailings dam. To what extent does flood control or weir structures affect the overtopping of a tailings dam?
	Q.2.5	Dam Type	Whether a tailings dam is constructed in multiple stages (raising) or single stages (such as retention dams) is expected to affect the overtopping of tailings dams. To what extent does the tailings dam construction technique affect the overtopping of a tailings dam?
Slope Instability	Q.3.1	Seismicity	The seismicity of the region where the tailings dam is constructed is expected to have an effect on the slope instability (structural failure) of the tailings dam. To what extent does seismicity affect the slope instability (structural failure) of a tailings dam?
	Q.3.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to affect the slope instability (structural failure) of the dam. To what extent does the construction material affect the slope instability (structural failure) of a tailings dam?
	Q.3.3	Seepage control	Seepage control in a tailings dam by means of a pump or liner is expected to have an impact on the slope instability (structural failure) of the dam. To what extent do seepage control practices affect the slope instability (structural failure) of a tailings dam?
	Q.3.4	Drainage facilities	Drainage (removal) of water accumulated in a tailings dam by means of drains or decants is expected to have an effect on the slope instability (structural failure) of the dam. To what extent do drainage practices affect the slope instability (structural failure) of a tailings dam?
	Q.3.5	Phreatic surface	Monitoring and control of the water table (phreatic surface) in deposited tailings in a tailings dam is expected to have an effect on the slope instability (structural failure) of the dam. To what extent does water table monitoring and control affect the slope instability (structural failure) of a tailings dam?
	Q.3.6	Height and inclination	The height and slope gradient of a tailings dam are expected to affect the slope instability (structural failure) of the dam. To what extent do dam height and slope gradient affect the slope instability (structural failure) of a tailings dam?
	Q.3.7	Erosion	The exposure of the tailings dam body to erosion is expected to have an effect on the slope instability (structural failure) of the dam. To what extent does erosion exposure affect the slope instability (structural failure) of a tailings dam?
	Q.3.8	Dam Type	The construction technique of the tailings dam is expected to affect the slope instability of the tailings dam. To what extent does the tailings dam construction technique affect the slope instability of a tailings dam?

3.4.2 Evaluation of the Survey Results

This section outlines the methodology used to assess the survey results and interpret the resulting outcomes.

i) Weighting Factor Determination:

Responses to similar questions may vary depending on the participants' competencies, perspectives, and levels of experience. Therefore, a weighting system is essential to assign appropriate significance to individual responses and to synthesize them into a generalized, representative score. Furthermore, the majority of the survey questions were asked to be responded with linguistic terms such as very low, low, moderate, high, and very high. Consequently, the way each participant interprets and quantifies these terms is a critical factor in evaluating their responses. Examples of expert weighting scores considered in various studies are presented in Table 3.4. Each participant is assigned a total score based on the cumulative evaluation of their attributes. The ratio of their individual total score to the cumulative total score of all participants determine the weighting assigned to each participant's responses.

Table 3.4 Some Literature Studies Using Expert Weighting Scores

Study	Attributes				Scores
	Title/ Designation	Experience	Education	Age	
Shi et al. (2018)	Senior academic	≥ 30 years	Doctoral	-	5
	Junior academic	20-29	Masters	-	4
	Engineer	10-19	Bachelor	-	3
	Technician	6-9	Technical	-	2
	Worker	≤5	School level	-	1
Cheliyan and Bhattacharyya (2018)	Professor / Senior Manager	≥ 30 years	Doctoral	>50	5
	Associate Professor / Manager	20-30	Masters	40-50	4
	Asst. Professor / Asst. Manager	10-20	Bachelors	30-40	3
	Lecturer / Sr. Officer	5-10	Technical	25-30	2
	Worker / Officer	< 5	School level	<25	1

The current thesis employs the expert scoring table presented in Table 3.5, developed specifically for the surveys, to assign scores to participants based on their professional titles, experience with TSF-related topics, educational background, and age.

Table 3.5 The Participant Weighting Scores Used in the Current Study

Title/ Designation	Attributes			Scores
	Experience	Education	Age	
Board Member, High-Level Manager or Equivalent	≥ 20 years	Doctoral	≥ 50	5
Senior Chief Engineer or Equivalent	[15-19]	Masters	[41-49]	4
Senior Engineer or Equivalent	[10-14]	Bachelor	[36-40]	3
Engineer, Mid-level Specialist or Equivalent	[5-9]	Technical	[30-35]	2
Other	<5	Under Grad	<30	1

As previously noted, twelve experts with diverse professional titles, varying levels of experience, and distinct educational backgrounds participated in the TSF Failure Potential survey, while seven experts contributed to the TSF Failure Consequences survey. The scores and weightings assigned by each participant were calculated as presented in Table 3.6 and Table 3.7, based on the scoring rubric outlined in Table 3.5. To preserve confidentiality, participants' personal information has been anonymized, and each expert is identified by a unique ID.

Table 3.6 Weighting Scores of Experts Participating in the Failure Consequences Survey

ID	Title	Title Score	Educational Level	Educational Level Score	Experience	Experience Score	Age	Age Score	Total	Weight
C#01	General Manager	5	Bachelors	3	34	5	61	5	18	16%
C#02	General Manager	5	Bachelors	3	16	4	53	5	17	15%
C#03	Managing Partner	5	Masters	4	36	5	55	5	19	17%
C#04	ESG Principal Consultant	4	Bachelors	3	19	4	42	4	15	13%
C#05	Chief Coordinator	4	Masters	4	7	2	41	4	14	12%
C#06	Manager	5	Bachelors	3	22	5	54	5	18	16%
C#07	Social Specialist	3	Masters	4	5	2	42	4	13	11%
Sum									114	

Table 3.7 Weighting Scores of Experts Participating in the Failure Potential Survey

ID	Title	Title Score	Educational Level	Educational Level Score	Experience	Experience Score	Age	Age Score	Total	Weight
FP#01	Chairman of the Board	5	Bachelors	3	14	3	35	2	13	8.33%
FP#02	Chairman of the Board	5	Bachelors	3	8	2	35	2	12	7.69%
FP#03	Senior Engineer	3	Masters	4	18	4	54	5	16	10.26%
FP#04	Senior Engineer	3	Bachelors	3	23	5	51	5	16	10.26%
FP#05	Senior Engineer	3	Bachelors	3	28	5	54	5	16	10.26%
FP#06	Environmental Manager	4	Bachelors	3	16	4	39	3	14	8.97%
FP#07	Assistant Professor	1	Doctoral	5	2	1	41	3	10	6.41%
FP#08	Senior Engineer	3	Bachelors	3	10	3	35	2	11	7.05%
FP#09	Senior Engineer	3	Masters	4	13	3	37	3	13	8.33%
FP#10	Chief Engineer	4	Bachelors	3	12	3	41	4	14	8.97%
FP#11	Senior Engineer	3	Masters	4	8	2	34	2	11	7.05%
FP#12	Environmental Manager	4	Bachelors	3	4	1	35	2	10	6.41%
Sum									156	

ii) Quantitative Ranges of the Linguistic Expressions:

Linguistic responses were collected from participants through the surveys. In such surveys, participants are typically allowed to use a scale with five to nine levels to ensure fair and consistent judgment (Liu et al., 2012; Cheliyan and Bhattacharyya, 2018). In the present study, five linguistic terms were utilized: very high, high, moderate, low, and very low. Prior to answering the survey questions, each participant was also asked to define these terms on a scale from 1 to 10 using a triangular distribution, an established method for representing expert uncertainty (Liu et al., 2012), specifying the minimum, most expected, and maximum values for each linguistic term. This procedure improves the precision and clarity of linguistic interpretations by linking qualitative assessments to explicit numerical ranges. Table 3.8 presents the participant-defined ranges for each linguistic term while their descriptive statistics are presented in Table 3.9.

Table 3.8 Ranges of Linguistic Expressions for Each Participant

ID	Linguistic Expressions														
	Very High (VH)			High (H)			Moderate (M)			Low (L)			Very Low (VL)		
	Min	Expected	Max	Min	Expected	Max	Min	Expected	Max	Min	Expected	Max	Min	Expected	Max
C#01	8	9	10	6	7	8	4	5	6	3	4	5	1	2	3
C#02	8	9	10	6	7	8	4	5	6	2	3	4	1	1	2
C#03	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
C#04	9	9	10	7	8	9	4	5	6	2	3	4	1	2	2
C#05	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
C#06	10	10	10	9	9	9	6	6	6	4	4	4	1	1	1
C#07	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
FP#01	9	9	10	7	8	8	4	5	6	3	4	4	1	2	3
FP#02	9	9	10	7	7	8	4	5	6	3	3	4	1	2	2
FP#03	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
FP#04	8	9	10	5	6	7	3	4	5	2	2	2	1	1	1
FP#05	8	9	10	6	7	9	4	5	6	2	3	4	1	2	3
FP#06	9	9	10	7	8	9	5	6	7	3	4	5	1	2	2
FP#07	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
FP#08	7	8	9	6	7	8	5	6	7	4	5	6	3	4	5
FP#09	8	9	10	6	7	8	4	5	6	2	3	4	1	1	2
FP#10	7	8	9	6	7	8	5	6	7	4	5	6	2	3	4
FP#11	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
FP#12	8	9	10	7	8	9	5	6	7	2	3	4	1	2	3

Table 3.9 Statistics of the Linguistic Expression Ranges

		Linguistic Expressions														
		Very High (VH)			High (H)			Moderate (M)			Low (L)			Very Low (VL)		
		Min	Expected	Max	Min	Expected	Max	Min	Expected	Max	Min	Expected	Max	Min	Expected	Max
C#	Mean	8.4	9.1	10.0	6.6	7.4	8.3	4.3	5.1	6.0	2.4	3.3	4.1	1.0	1.7	2.4
	StDev	0.7	0.3	0.0	1.0	0.7	0.5	0.7	0.3	0.0	0.7	0.5	0.3	0.0	0.5	0.7
	Median	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
	Mod	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
FP#	Mean	8.1	8.8	9.8	6.3	7.2	8.2	4.3	5.3	6.3	2.6	3.4	4.3	1.3	2.1	2.8
	StDev	0.6	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.9	1.0	0.6	0.8	1.0
	Median	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3
	Mod	8	9	10	6	7	8	4	5	6	2	3	4	1	2	3

iii) Responses of the Participants:

The participants responded to the questions specified in Appendix A and Appendix B using a five-point verbal rating scale including very high (VH), high (H), moderate (M), low (L), and very low (VL) and expressed the influence of the relevant parameters on the main events. The responses for the TSF Failure Consequences survey are listed in Table 3.10, While the responses for the TSF Failure Potential Survey are given in Table 3.11.

Table 3.10 Linguistic Responses for the Questionnaire of the TSF Failure Consequences Survey

Sub-Parameters	Question Code	C#01	C#02	C#03	C#04	C#05	C#06	C#07
<i>Human Health - Severity</i>								
Toxicity	Q.2.1	VH	VH	H	VH	VH	VH	H
Damage to infrastructure and facilities	Q.2.2	VH	H	M	H	H	VH	H
Resilience of residences	Q.2.3	H	VH	L	M	M	H	H
Quickness of rescue services	Q.2.4	VH	H	H	H	H	H	VH
Vulnerability of the region to natural hazards	Q.2.5	M	H	H	L	VH	H	M
<i>Human Health – Degree of Preparedness</i>								
Emergency planning	Q.3.1	VH	H	VH	H	H	M	VH
First aid opportunities	Q.3.2	H	H	VH	H	M	M	H
Early warning	Q.3.3	VH	VH	H	L	VH	H	VH
Training	Q.3.4	M	VH	H	H	M	M	H
<i>Social and Economic Life - Vulnerability</i>								
Dependency on Mining	Q.4.1	H	H	H	H	VH	L	M
Diversity of Economic Activities	Q.4.2	H	H	L	L	VH	VH	H
Proportion of Vulnerable Groups	Q.4.3	M	VH	M	M	VH	VH	H
Existence of Indigenous People	Q.4.4	H	VH	H	L	H	VH	M
<i>Social and Economic Life - Social Disturbance</i>								
Unrest	Q.5.1	VH	M	VH	H	H	VH	H
Displacement	Q.5.2	VH	VH	VH	VH	H	VH	VH
Poverty	Q.5.3	VH	M	H	VH	VH	M	H
<i>Social and Economic Life – Economic Support</i>								
Compensation	Q.6.1	VH	H	VH	H	M	H	H
Insurance	Q.6.2	VH	M	VH	VH	M	H	H
Donation	Q.6.3	H	M	M	L	L	L	L

Table 3.11 Linguistic Responses for the Questionnaire of the TSF Failure Potential Survey

Sub-Parameters	Question Code	FP#01	FP#02	FP#03	FP#04	FP#05	FP#06	FP#07	FP#08	FP#09	FP#10	FP#11	FP#12
Active Dam Failure Modes - Overtopping													
Extreme hydraulic events	Q.2.1	H	M	M	M	H	L	VH	H	VH	H	L	L
Natural hazards	Q.2.2	VH	H	M	M	H	VH	VH	H	VH	H	L	M
Excess water storage	Q.2.3	H	H	H	VH	VH	VH	M	M	M	M	M	L
Flood control facilities	Q.2.4	H	H	H	VH	VH	VH	M	L	VH	M	VH	VL
Dam type	Q.2.5	VH	M	H	H	VH	M	M	H	M	H	H	L
Active Dam Failure Modes – Slope Instability													
Seismicity	Q.3.1	VH	VH	VH	H	H	H	VH	VH	H	H	M	H
Construction material	Q.3.2	VH	VH	VH	H	VH	VH	VH	H	VH	H	H	H
Seepage control	Q.3.3	M	M	M	H	H	H	H	M	H	H	H	VH
Drainage facilities	Q.3.4	L	M	M	H	H	H	H	H	H	H	H	M
Phreatic surface	Q.3.5	L	M	L	H	VH	M	H	M	H	M	H	L
Height and inclination	Q.3.6	VH	H	H	VH	VH	H	VH	H	VH	H	H	H
Erosion	Q.3.7	H	H	VH	H	H	VH	H	H	H	M	H	VH
Dam type	Q.3.8	VH	H	VH	H	VH	M	VH	H	H	H	H	H
Active Dam Failure Modes – Internal Erosion													
Seepage control	Q.4.1	M	L	H	H	M	VH	H	M	H	L	H	H
Construction material	Q.4.2	VH	H	H	VH	H	L	VH	M	L	L	H	VH
Phreatic surface	Q.4.3	L	M	M	H	H	M	H	M	VH	M	H	H
Dry beach location and width	Q.4.4	M	L	VL	H	M	M	H	M	H	M	M	M
Dam type	Q.4.5	VH	H	H	H	VH	M	VH	H	M	H	M	VH
Active Dam Failure Modes – Foundation Failure													
Seepage control	Q.5.1	M	L	M	H	VH	H	H	L	H	M	H	VH
Drainage facilities	Q.5.2	L	M	M	H	H	M	H	M	H	H	H	M
Foundation properties	Q.5.3	VH	H	H	H	VH	H	VH	VH	VH	H	VH	VH
Groundwater condition	Q.5.4	H	M	H	VH	H	VH	VH	H	VH	M	VH	VH
Seismicity	Q.5.5	VH	VH	H	H	H	VH	H	H	H	H	VH	H
Subsidence	Q.5.6	H	H	H	VH	H	VH	H	H	H	H	VH	H
Dam type	Q.5.7	VH	H	M	H	VH	M	H	H	H	VH	VH	H

Table 3.11 Linguistic Responses for the Questionnaire of the TSF Failure Potential Survey (cont'd)

Sub-Parameters	Question Code	FP#01	FP#02	FP#03	FP#04	FP#05	FP#06	FP#07	FP#08	FP#09	FP#10	FP#11	FP#12
<i>Active Dam Management - Dam Safety Management</i>													
Dam safety monitoring	Q.6.1	VH	H	H	VH	VH	VH	VH	VH	H	VH	VH	H
Warning system	Q.6.2	M	H	H	VH	VH	VH	VH	H	H	VH	H	VH
Emergency planning	Q.6.3	M	M	M	M	VH	VH	VH	H	VH	M	VH	M
Training and safety culture of workers	Q.6.4	H	M	H	H	H	H	VH	H	VH	H	VH	H
Supervision and responsibility	Q.6.5	H	H	H	H	H	H	VH	H	VH	H	VH	H
<i>Active Dam Management - Internal Management</i>													
Design and construction	Q.7.1	VH	VH	VH	VH	VH	L	VH	H	H	H	VH	VH
Qualification and Experience	Q.7.2	H	H	H	VH	VH	H	VH	VH	H	VH	VH	H
Maintenance practices	Q.7.3	H	H	H	VH	M	H	H	H	H	VH	H	H
<i>Active Dam Management - External Management</i>													
Seepage control	Q.8.1	VH	VH	H	VH	VH	H		H	H	VH	H	M
Construction material	Q.8.2	VH	H	VH	VH	H	H		H	H	H	H	M
Phreatic surface	Q.8.3	VH	VH	VH	VH	H	M		VH	H	H	H	H
<i>Closed Dam Failure Modes - Overtopping</i>													
Extreme hydraulic events	Q.10.1	H	M	L	L	M	L	VH	H	H	L	L	M
Natural hazards	Q.10.2	VH	H	L	L	M	H	H	H	H	L	L	H
Flood control facilities	Q.10.3	H	H	H	L	H	M	M	M	VH	M	L	M
<i>Closed Dam Failure Modes – Slope Instability</i>													
Seismicity design	Q.11.1	VH	H	VH	H	H	VH	H	VH	H	M	H	L
Construction material	Q.11.2	VH	H	H	H	VH	VH	VH	VH	VH	H	H	M
Seepage and drainage measures	Q.11.3	H	L	H	M	VH	M	H	H	H	L	H	H
Height and inclination	Q.11.4	VH	H	M	M	VH	M	VH	VH	VH	M	L	M
Erosion measures	Q.11.5	H	L	H	H	H	H	H	H	H	H	L	VH
Dam type	Q.11.6	VH	H	H	M	VH	M	VH	VH	H	H	M	H

Table 3.11 Linguistic Responses for the Questionnaire of the TSF Failure Potential Survey (cont'd)

Sub-Parameters	Question Code	FP#01	FP#02	FP#03	FP#04	FP#05	FP#06	FP#07	FP#08	FP#09	FP#10	FP#11	FP#12
<i>Closed Dam Failure Modes – Internal Erosion</i>													
Seepage and drainage measures	Q.12.1	H	M	VH	L	H	H	VH	H	M	L	H	H
Construction material	Q.12.2	VH	H	H	H	L	VH	VH	H	VH	H	H	M
Phreatic surface control	Q.12.3	M	M	VH	H	M	M	H	VH	VH	L	H	M
Dam Type	Q.12.4	H	VH	H	M	H	M	H	H	H	L	H	H
<i>Closed Dam Failure Modes – Foundation Failure</i>													
Seepage measures	Q.13.1	M	M	L	L	VH	VH	H	H	H	H	H	VH
Foundation properties	Q.13.2	VH	H	VH	VH	VH	VH	VH	H	VH	H	H	VH
Groundwater condition	Q.13.3	H	M	H	VH	H	M	H	H	H	M	H	H
Seismicity measure	Q.13.4	VH	VH	H	H	H	M	H	VH	H	H	H	M
Subsidence measure	Q.13.5	H	H	H	H	M	M	M	H	H	H	H	H
Dam Type	Q.13.6	H	VH	M	M	VH	M	H	H	M	L	VH	H
<i>Post Closure Management</i>													
Supervision	Q.14.1	H	H	M	VH	H	M	H	H	H	H	H	H
Monitoring and warning system	Q.14.2	VH	H	H	VH	H	M	VH	H	H	H	M	H
Regulatory control at closure	Q.14.3	H	M	H	VH	H	M	H	H	H	H	H	M
Closure planning	Q.14.4	H	H	H	VH	H	VH	VH	VH	VH	H	H	H
Capital investment	Q.14.5	VH	H	L	VH	H	H	H	H	H	H	H	H
<i>Abandoned Dam Failure Modes - Overtopping</i>													
Extreme hydraulic events	Q.16.1	H	H	VH	H	VH	M	VH	H	H	L	M	M
Natural hazards	Q.16.2	VH	VH	H	H	H	H	VH	VH	H	M	H	M
Flood control facilities	Q.16.3	H	H	M	H	H	H	H	H	VH	L	M	H
<i>Abandoned Dam Failure Modes - Slope Instability</i>													
Seismicity design	Q.17.1	VH	H	VH	H	H	VH	H	VH	H	H	M	H
Construction material	Q.17.2	VH	H	H	VH	H	VH	VH	H	VH	H	VH	VH
Seepage and drainage measures	Q.17.3	H	L	M	VH	M	H	H	H	VH	L	M	H
Height and inclination	Q.17.4	VH	VH	H	VH	H	M	VH	VH	H	H	M	H
Erosion measures	Q.17.5	H	L	M	VH	H	H	H	H	H	H	H	VH
Dam Type	Q.17.6	VH	H	H	VH	VH	M	VH	VH	H	H	M	H

Table 3.11 Linguistic Responses for the Questionnaire of the TSF Failure Potential Survey (cont'd)

Sub-Parameters	Question Code	FP#01	FP#02	FP#03	FP#04	FP#05	FP#06	FP#07	FP#08	FP#09	FP#10	FP#11	FP#12
<i>Abandoned Dam Failure Modes – Internal Erosion</i>													
Seepage and drainage measures	Q.18.1	H	H	VH	H	VH	M	VH	H	H	L	M	M
Construction material	Q.18.2												
Phreatic surface control measures	Q.18.3	VH	VH	H	H	H	H	VH	VH	H	M	H	M
Dam Type	Q.18.4	H	H	M	H	H	H	H	H	VH	L	M	H
<i>Abandoned Dam Failure Modes – Foundation Failure</i>													
Seepage measures	Q.19.1	VH	H	VH	H	H	VH	H	VH	H	H	M	H
Foundation properties	Q.19.2	VH	H	H	VH	H	VH	VH	H	VH	H	VH	VH
Groundwater condition	Q.19.3	H	L	M	VH	M	H	H	H	VH	L	M	H
Seismicity measure	Q.19.4	VH	VH	H	VH	H	M	VH	VH	H	H	M	H
Subsidence measure	Q.19.5	H	L	M	VH	H	H	H	H	H	H	H	VH
Dam Type	Q.19.6	VH	H	H	VH	VH	M	VH	VH	H	H	M	H
<i>Abandoned Dam Management</i>													
Monitoring and warning system	Q.20.1	VH	H	VH	H	H	VH	H	VH	H	H	M	H
Regulatory control	Q.20.2	VH	H	H	VH	H	VH	VH	H	VH	H	VH	VH
Dam behavior	Q.20.3	VH	H	H	VH	VH	M	VH	VH	H	H	M	H

iv) Aggregation of the Fuzzy Numbers

The responses were aggregated using individual responses and weighting scores of the participants given in Table 3.12.

Table 3.12 Aggregated Values for the Weighting Scores of the Failure Potential Parameters

Question Code	Min	Most Expected	Max	Average	Weights	Question Code	Min	Most Expected	Max	Average	Weights
Q.2.1	5.134	6.030	6.993	6.052	18.1%	Q.11.1	6.470	7.331	8.321	7.374	17.4%
Q.2.2	6.041	6.920	7.909	6.957	20.8%	Q.11.2	7.027	7.866	8.866	7.920	18.7%
Q.2.3	5.799	6.693	7.682	6.725	20.1%	Q.11.3	5.442	6.344	7.316	6.368	15.0%
Q.2.4	6.186	7.029	8.002	7.072	21.1%	Q.11.4	5.834	6.715	7.704	6.751	15.9%
Q.2.5	5.728	6.634	7.623	6.662	19.9%	Q.11.5	5.827	6.721	7.696	6.748	15.9%
Q.3.1	6.838	7.694	8.694	7.742	13.4%	Q.11.6	6.312	7.197	8.197	7.235	17.1%
Q.3.2	7.355	8.171	9.171	8.232	14.2%	Q.12.1	5.530	6.416	7.384	6.443	24.1%
Q.3.3	5.701	6.635	7.635	6.657	11.5%	Q.12.2	6.333	7.193	8.176	7.234	27.0%
Q.3.4	5.457	6.387	7.373	6.406	11.1%	Q.12.3	5.558	6.459	7.444	6.487	24.2%
Q.3.5	4.868	5.774	6.732	5.791	10.0%	Q.12.4	5.677	6.590	7.575	6.614	24.7%
Q.3.6	7.049	7.893	8.893	7.945	13.7%	Q.13.1	5.647	6.518	7.483	6.550	15.5%
Q.3.7	6.541	7.422	8.422	7.462	12.9%	Q.13.2	7.519	8.321	9.321	8.387	19.8%
Q.3.8	6.717	7.582	8.582	7.627	13.2%	Q.13.3	5.925	6.846	7.846	6.873	16.2%
Q.4.1	5.291	6.200	7.172	6.221	19.7%	Q.13.4	6.365	7.256	8.256	7.293	17.2%
Q.4.2	5.721	6.569	7.526	6.605	20.9%	Q.13.5	5.737	6.675	7.675	6.696	15.8%
Q.4.3	5.238	6.170	7.156	6.188	19.6%	Q.13.6	5.623	6.522	7.507	6.551	15.5%
Q.4.4	4.314	5.263	6.225	5.267	16.7%	Q.14.1	6.053	6.969	7.969	6.997	19.3%
Q.4.5	6.339	7.223	8.223	7.262	23.0%	Q.14.2	6.388	7.276	8.276	7.313	20.2%
Q.5.1	5.464	6.363	7.339	6.389	12.5%	Q.14.3	5.976	6.895	7.895	6.922	19.1%
Q.5.2	5.137	6.080	7.066	6.094	11.9%	Q.14.4	7.002	7.850	8.850	7.901	21.8%
Q.5.3	7.237	8.064	9.064	8.122	15.9%	Q.14.5	6.215	7.092	8.075	7.127	19.7%
Q.5.4	6.786	7.638	8.638	7.687	15.0%	Q.16.1	5.966	6.849	7.834	6.883	32.9%
Q.5.5	6.838	7.701	8.701	7.746	15.2%	Q.16.2	6.483	7.363	8.363	7.403	35.3%
Q.5.6	6.732	7.605	8.605	7.647	15.0%	Q.16.3	5.728	6.637	7.622	6.662	31.8%
Q.5.7	6.500	7.375	8.375	7.417	14.5%	Q.17.1	6.744	7.608	8.608	7.653	17.3%
Q.6.1	7.484	8.288	9.288	8.354	21.9%	Q.17.2	7.272	8.096	9.096	8.155	18.4%
Q.6.2	7.024	7.862	8.862	7.916	20.7%	Q.17.3	5.428	6.323	7.295	6.349	14.3%
Q.6.3	5.964	6.855	7.855	6.891	18.1%	Q.17.4	6.658	7.522	8.522	7.567	17.1%
Q.6.4	6.496	7.382	8.382	7.420	19.4%	Q.17.5	6.068	6.959	7.947	6.991	15.8%
Q.6.5	6.650	7.530	8.530	7.570	19.8%	Q.17.6	6.705	7.565	8.565	7.611	17.2%
Q.7.1	7.143	7.941	8.926	8.004	34.2%	Q.18.1	6.343	7.206	8.191	7.247	24.2%
Q.7.2	7.167	8.000	9.000	8.056	34.4%	Q.18.2	7.049	7.893	8.893	7.945	26.6%
Q.7.3	6.397	7.291	8.291	7.326	31.3%	Q.18.3	6.409	7.294	8.294	7.333	24.5%
Q.8.1	6.556	7.343	7.878	7.259	34.2%	Q.18.4	6.473	7.342	8.342	7.386	24.7%
Q.8.2	6.250	7.065	7.600	6.972	32.9%	Q.19.1	5.701	6.604	7.589	6.631	15.3%
Q.8.3	6.469	6.802	7.674	6.982	32.9%	Q.19.2	7.531	8.331	9.331	8.398	19.3%
Q.10.1	4.212	5.100	6.024	5.112	30.4%	Q.19.3	6.015	6.902	7.887	6.934	16.0%
Q.10.2	4.858	5.739	6.678	5.758	34.2%	Q.19.4	6.885	7.744	8.744	7.791	17.9%
Q.10.3	5.012	5.932	6.903	5.949	35.4%	Q.19.5	5.784	6.711	7.711	6.735	15.5%
						Q.19.6	6.024	6.909	7.892	6.942	16.0%
						Q.20.1	6.718	7.577	8.577	7.624	34.4%
						Q.20.2	6.141	7.045	8.045	7.077	31.9%
						Q.20.3	6.567	7.455	8.455	7.493	33.8%

A sample calculation is provided below to show the aggregation of minimum, most likely, and maximum values for the Extreme Hydraulic Event (Q.2.1), which influences the overtopping failure mode of active TSFs.

Question: Q.2.1 Extreme hydraulic (meteorological) events such as tropical rainfall, heavy snowmelt or hurricanes in the area where the tailings dam is built are expected to have an impact on tailings dam overtopping. Accordingly, to what extent does extreme hydraulic events affect the overtopping of a tailings dam?

a) For the participants involved in TSF Failure Potential Survey, the means of Minimum, Most Expected, and Maximum values for linguistic variables from Table 3.9:

$$\{VH_{\min}, H_{\min}, M_{\min}, L_{\min}, VL_{\min}\} = \{8.1, 6.3, 4.3, 2.6, 1.3\}$$

$$\{VH_{\exp}, H_{\exp}, M_{\exp}, L_{\exp}, VL_{\exp}\} = \{8.8, 7.2, 5.3, 3.4, 2.1\}$$

$$\{VH_{\max}, H_{\max}, M_{\max}, L_{\max}, VL_{\max}\} = \{9.8, 8.2, 6.3, 4.3, 2.8\}$$

b) Expert weightings of the experts from Table 3.7:

$$\text{Expert}_i(\%): \{8.33, 7.69, 10.26, 10.26, 10.26, 8.97, 6.41, 7.05, 8.33, 8.97, 7.05, 6.41\}$$

$$\text{where } \sum_{i=1}^{12} \text{Expert}_i(\%) = 100\%$$

c) Twelve responses to Q.2.1 from Table 3.11:

$$\text{Response}_i: \{H, M, M, M, H, L, VH, H, VH, H, L, L\} \text{ where } i = 1 \dots 12$$

d) Calculation of $Q. 2.1_{\min}$, $Q. 2.1_{\exp}$, and $Q. 2.1_{\max}$:

$$Q. 2.1_{\min} = H_{\min} \times \text{Expert}_1 + M_{\min} \times \text{Expert}_2 + M_{\min} \times \text{Expert}_3 + M_{\min} \times \text{Expert}_4 + \dots \\ + L_{\min} \times \text{Expert}_{12}$$

$$Q. 2.1_{\min} = [(6.3 \times 8.33) + (4.3 \times 7.69) + (4.3 \times 10.26) + (4.3 \times 10.26) + (6.3 \times 10.26) + (2.6 \times 8.97) \\ + (8.1 \times 6.41) + (6.3 \times 7.05) + (8.1 \times 8.33) + (6.3 \times 8.97) + (2.6 \times 7.05) \\ + (2.6 \times 6.41)]/100 = 5.134$$

$$Q. 2.1_{\exp} = [(7.2 \times 8.33) + (5.3 \times 7.69) + (5.3 \times 10.26) + (5.3 \times 10.26) + (7.2 \times 10.26) + (3.4 \times 8.97) \\ + (8.8 \times 6.41) + (7.2 \times 7.05) + (8.8 \times 8.33) + (7.2 \times 8.97) + (3.4 \times 7.05) \\ + (3.4 \times 6.41)]/100 = 6.030$$

$$Q. 2.1_{\max} = [(8.2 \times 8.33) + (6.3 \times 7.69) + (6.3 \times 10.26) + (6.3 \times 10.26) + (8.2 \times 10.26) + (4.3 \times 8.97) \\ + (9.8 \times 6.41) + (8.2 \times 7.05) + (9.8 \times 8.33) + (8.2 \times 8.97) + (4.3 \times 7.05) \\ + (4.3 \times 6.41)]/100 = 6.993$$

$$Q. 2.1_{\text{average}} = \frac{Q. 2.1_{\min} + Q. 2.1_{\text{most expected}} + Q. 2.1_{\max}}{3} = \frac{5.134 + 6.030 + 6.993}{3} = 6.052$$

v) Calculate parametric weight of extreme hydraulic events (Q. 2.1) on Overtopping failure mode for an active TSF:

$$Q.2.1_{weight} = \frac{Q.2.1_{average}}{Q.2.1_{average} + Q.2.2_{average} + Q.2.3_{average} + Q.2.4_{average} + Q.2.5_{average}} = \frac{6.052}{6.052 + 6.957 + 6.725 + 7.072 + 6.662} = 18.1\%$$

The expert survey indicates that, among the overtopping failure parameters, namely extreme hydraulic events, natural hazards, excess water storage, flood control facilities, and dam type, extreme hydraulic events are with an effectiveness rate of 18.1%. This methodology is also applied to the remaining parameters in the failure potential survey. Furthermore, using the same approach, the analysis results of the TSF failure consequences survey are obtained, as presented in Table 3.13.

Table 3.13 Aggregated Values for the Weighting Scores of the Failure Consequences Parameters

Question Code	Min	Most Expected	Max	Average	Weights	Question Code	Min	Most Expected	Max	Average	Weights
Q.2.1	7.907	8.662	9.519	8.696	23.4%	Q.4.1	5.885	6.724	7.581	6.730	24.3%
Q.2.2	6.777	7.589	8.446	7.604	20.5%	Q.4.2	5.857	6.674	7.531	6.688	24.1%
Q.2.3	5.576	6.412	7.269	6.419	17.3%	Q.4.3	6.327	7.123	7.980	7.143	25.8%
Q.2.4	7.076	7.895	8.752	7.908	21.3%	Q.4.4	6.336	7.149	8.006	7.164	25.8%
Q.2.5	5.633	6.472	7.330	6.478	17.5%	Q.5.1	7.127	7.915	8.772	7.938	32.6%
Q.3.1	7.025	7.820	8.677	7.840	26.6%	Q.5.2	8.201	8.932	9.789	8.974	36.8%
Q.3.2	6.239	7.073	7.930	7.081	24.0%	Q.5.3	6.635	7.434	8.291	7.453	30.6%
Q.3.3	7.036	7.816	8.673	7.842	26.6%	Q.6.1	6.893	7.704	8.561	7.720	38.9%
Q.3.4	5.846	6.682	7.539	6.689	22.7%	Q.6.2	6.797	7.589	8.446	7.611	38.3%
						Q.6.3	3.669	4.526	5.383	4.526	22.8%

3.5 Consequence Model Parameters

A tailings dam failure can result in a wide range of consequences. The consequence assessment for downstream communities will address the impacts on:

- i) Human Health
- ii) Social and Economic Life
- iii) Environment

Total consequence of an event is determined as the sum of these impacts. It is crucial to note that the scoring rubrics in the following sections, which are used to assess the parametric values of factors and sub-factors, have been established based on the professional evaluations of experts with experience in the relevant fields. Preferably the experts should be selected among social scientists, health and safety practitioners, environmental specialists, engineers or managers with experience in monitoring or assessing the impacts of mining activities on nearby communities.

3.5.1 Human Health

The consequences to human health are assessed in two categories: *Potential Loss of Life* (PLL) and *Potential Loss of Health* (PLH). The assessment of PLL and PLH is based on similar approach of tailings dam classification of International Commission on Large Dams (ICOLD). In Bulletin 194 on Tailings Dam Safety, ICOLD utilizes the concept of Population at Risk (PAR). Population at Risk is used to denote the number of individuals who may be exposed to the hazard. PAR is used to refer to the number of people living in areas that are likely to be affected by flooding. This term includes both residents of the affected area, as well as those who may be present for a limited time or on an occasional basis. This could include seasonal or recreational visitors, as well as temporary travelers (ICOLD, 2025).

For analysis of PLL and PLH, the flooded area is divided into two distinct zones.

- i. Red Zone
- ii. Yellow Zone

Potential Loss of Life is considered to be occurred in areas where the slurry level exceeds 0.7 meters above ground or where slurry velocities exceed 0.5 m/s, according to EU Commission Decision, 2009/337/EC. This area is designated as the Red Zone. PLL is quantified by a function PAR, the number of individuals who could potentially be present within the Red Zone.

On the other hand, areas where the slurry depth is less than 0.7 meters and slurry velocities do not exceed 0.5 m/s are classified as exposing to a serious danger to health. This area is designated as the Yellow Zone, where individuals are considered at risk of experiencing prolonged illnesses and disabilities, thus representing a serious health hazard. *Potential Loss of Health* is quantified as a function of PAR in Yellow Zone.

Individuals in flooded area (Red and Yellow zones) is divided into following two groups:

- i. Vulnerable group
- ii. Active group

Vulnerable group include children and the elderly, while the active group consists of individuals who are not classified as vulnerable but still affected by the event. Those groups are called as *Vulnerable People at Risk* and *Active People at Risk*, and they are designated as VPAR and APAR, respectively. Sum of VPAR and APAR gives the number of *People at Risk* (PAR).

PLL is estimated by a function of PAR in Red Zone, *Severity Factor*, and *Degree of Preparedness* in Equation (3.1)

$$PLL = (PAR \text{ in Red Zone}) * (1 - (Degree \text{ of Preparedness} - Severity \text{ Factor}))/2 \quad (3.1)$$

In a same manner, PLH is the number of people with serious health hazard and is estimated as a function PAR in Yellow Zone, *Severity Factor*, and *Degree of Preparedness* (Equation (3.2)). Additionally, apart from PLL, rest of the PAR in Red

Zone is deemed as PLH. In other words, if people in Red Zone do not loss their lives, they are presumed as lost their health.

$$PLH = [(PAR \text{ in Yellow Zone }) * (1 - (\text{Degree of Preparedness} - \text{Severity Factor}))/2] + [(PAR \text{ in Red Zone}) - (PLL)] \quad (3.2)$$

Severity Factor

Under specific conditions, the consequences in the yellow region are expected to increase. This tendency is quantified using a Severity Factor derived from parameters such as damage to critical infrastructure (e.g., main roads, medical facilities), the toxicity of the tailings, quickness of external rescue services, resilience of residences, and the region's vulnerability to natural hazards. *Severity Factor* is estimated as weighted sum of those parameters given in Equation (3.3).

$$\begin{aligned} \text{Severity Factor} = & [0.23(\text{Toxicity}) \\ & + 0.21(\text{Damage to Infrastructure and Facilities}) \\ & + 0.21(\text{Quickness of rescue services}) \\ & + 0.17(\text{Resilience of residences}) \\ & + 0.18(\text{Vulnerability to Natural Hazards})]/2 \end{aligned} \quad (3.3)$$

It should be noted that related scores in Table 3.14 would be inserted to associated parameters in Equation (3.3) and weighted sum of parameters is normalized dividing the term by the maximum score (2) in Table 3.14. As a result, *Severity Factor* takes values between 0 and 1.

Tailings flow containing substances that can cause acute or chronic health problems determine the toxicity level and toxic tailings increase severity factor. Damage to main roads or a medical unit will increase severity of the event preventing rescue opportunities. Type of construction material determine the strength of houses. If houses are built using weak material, they are prone to be damaged or demolished.

Limit values of “Quickness of rescue services” in Table 3.14 is determined through expert evaluation. Expected duration for rescue services to arrive at the site to reduce the severity of the incident is 18 minutes. On the other hand, maximum duration for

rescue services to reach at the site to be effective is estimated as 50 minutes by experts.

In Table 3.14, multiple parameters within the same criteria may be selected, provided that the maximum score is not exceeded.

Table 3.14 Severity Factor Index

Parameter (Max Score)	Scoring Rubric		
Toxicity (2)	Tailings containing substances causing acute health problems or death 2	Tailings containing substances causing chronic health problems 1	Inert tailings 0
Damage to infrastructure and facilities (Total 2)	Main roads are damaged 1	Medical unit is damaged (or no medical unit) 1	None 0
Quickness of rescue services (2)	> 50 min. 2	≥ 18 min. 1	< 18 min. 0
Resilience of residences (2)	Residences are mostly constructed with weak materials (clay, brick etc.) 2	Residences are mostly constructed with strong materials (steel, reinforced concrete etc.) 1	No residence 0
Vulnerability of the region to natural hazards (Total 2)	Vulnerable to natural floods 1	Vulnerable to earthquakes 1	None 0

Degree of Preparedness

The community's preparedness for a tailings dam failure event mitigates the potential consequences and is assessed as the *Degree of Preparedness* in Equation (3.4). This degree is influenced by factors such as the availability of emergency plans, access to first aid opportunities, the presence of an early warning system, and the extent of training provided to community members. The Degree of Preparedness is determined by summing the scores assigned to these parameters valued in Table 3.15.

$$\text{Degree of Preparedness} = [0.27(\text{Emergency Planning}) + 0.24(\text{First Aid Opportunities}) + 0.26(\text{Early Warning System}) + 0.23(\text{Training})]/2 \quad (3.4)$$

It should be noted in Equation (3.4) weighted sum of factors is normalized dividing the term by the maximum score (2) in Table 3.15. As a result, *Degree of Preparedness* takes values between 0 and 1.

Having emergency plans by mine owner or the authorities increases the preparedness of the community. In addition, setting up an early warning system or having sufficient time to warn the people before the tailings flow reaches are critical to be prepared for such an event. Available first aid opportunities like existence of a medical unit or having first aid kits increases degree of preparedness. Furthermore, a trained community is expected to be less impacted by the failure event since community members know how to behave or take action during and after the failure event.

Table 3.15 Degree of Preparedness Index

Parameter (Max Score)	Scoring Rubric		
Emergency planning (Total 2)	Mine owner has an emergency plan 1	Local authority or government has an emergency plan 1	None 0
First aid opportunities (2)	Medical unit exists in affected area 2	Only first aid kits are available 1	None 0
Early warning (2)	There is an early warning system in affected area 2	Sufficient reach time of flow for people to be warned 1	None 0
Training (2)	Community members have been trained 2	Community members have been informed 1	None 0

After determining the values of *Severity Factor* and *Degree of Preparedness*, the number of active people and vulnerable people lost their health due to a tailings dam failure is estimated by Equations (3.5) and (3.6), respectively.

$$\begin{aligned}
 &\text{Active People Lost Health} \\
 &= \text{APAR in Yellow Zone} * (1 \\
 &\quad - (\text{Degree of Preparedness} - \text{Severity Factor}))/2
 \end{aligned}
 \tag{3.5}$$

$$\begin{aligned}
&\text{Vulnerable People Lost Health} \\
&= \text{VPAR in Yellow Zone} * (1 \\
&\quad - (\text{Degree of Preparedness} - \text{Severity Factor}))/2
\end{aligned} \tag{3.6}$$

The total number of people lost their health is the sum of the number of active people lost health and vulnerable people lost their health during incident (Equation (3.7)).

$$PLH = \text{Active People Lost Health} + \text{Vulnerable People Lost Health} \tag{3.7}$$

Equations (3.5) and (3.6) predicts that if a community is fully prepared to a failure event and the event is not severe, the number of affected people is 0, on the other hand if the community is not prepared and the event is severe, all the people in the zone are assumed to have prolonged illnesses or disabilities. In a same manner if the severity factor and degree of preparedness are equal, then half of the people are affected by the event.

The consequence factor for *Human Health* is calculated as function of *PLL* and *PLH* given in Equation (3.8).

$$\text{Human Health} = \log(PLL + PLH) \tag{3.8}$$

where $PLL, PLH > 0$. It should be noted that if values of both *PLL* and *PLH* is 0 then *Human Health* also takes the value of 0, which means that there is no impact on human health.

3.5.2 Social and Economic Life

Individuals in affected community are divided into two groups namely vulnerable group and active group. Vulnerable group include children and the elderly, and they are assumed to be not in active economic life. On the other hand, the active group consists of individuals who are in the active economic life and not classified as vulnerable.

The failure of tailings dams can lead to a range of significant social and economic consequences. Flood waves may destroy residential properties, damage infrastructure and public buildings. Such an event can result in various forms of income loss, including the destruction of land, the displacement of workplaces, and the disruption of labor and wages. A tailings dam failure can have a profound and devastating impact on the social structure of downstream communities. It can result in fatalities and injuries, while survivors may be forced to migrate due to the destruction of public services, widespread damage, loss of economic activities, and rising unemployment. In certain instances, survivors may also face forced displacement as a result of government-mandated evacuations. In brief, displacement, poverty, and social unrest can significantly disrupt community life and social structures (*Social Disturbance*). However, economic support mechanisms such as insurance payouts, compensation from mine operators and/or government authorities, and donations from non-governmental organizations (NGOs) or the public can help mitigate these adverse economic impacts (*Economic Support*).

Vulnerability of a community is another important factor in estimating social and economic impact of an tailings dam failure event. Vulnerability is community's resistance to exposure to an adversely affected event or capacity to overcome an adverse situation. In other words, the higher the vulnerability of a community, the more susceptible it is to social and economic impacts.

Vulnerability Factor

The vulnerability of a community to a tailings dam failure is influenced by factors such as the diversity of main economic activities, dependency on mining, the proportion of vulnerable groups within the population, and presence of indigenous people in the community (Equation (3.9)). *Diversity of Economic Activities* is measured by reciprocal of the number of main distinct sectors present in the community. A greater diversity of economic activities inherently indicates lower community vulnerability, as it suggests a reduced reliance on a single industry. On the other hand, *Dependency on Mining* is assessed by the ratio of individuals

employed in the mining sector to the total workforce in the community. A higher dependency on mining increases the community's vulnerability, as disruptions in the mining industry are likely to have a more significant impact. In addition, vulnerable groups within the community are primarily composed of children and the elderly. A higher *Proportion of Vulnerable Groups* in the population increases the overall vulnerability of the community. Additionally, *Existence of Indigenous People* in the affected area is another component of vulnerability, since their life styles are highly dependent on that area. If indigenous people are not present, then Equation 3.10 is valid.

The extent of resistance experienced by the community to a tailings dam failure event is determined by its vulnerability, which can be quantified as a weighted sum of aforementioned factors.

$$\begin{aligned} \text{Vulnerability}_{\text{indigenous}} &= 0.24(\text{Dependency on Mining}) \\ &+ 0.24(\text{Diversity of Economic Activities}) \\ &+ 0.26(\text{Proportion of Vulnerable Groups}) \\ &+ 0.26(\text{Existence of Indigenous People}) \end{aligned} \quad (3.9)$$

$$\begin{aligned} \text{Vulnerability}_{\text{non-indigenous}} &= 0.33(\text{Dependency on Mining}) \\ &+ 0.33(\text{Diversity of Economic Activities}) \\ &+ 0.34(\text{Proportion of Vulnerable Groups}) \end{aligned} \quad (3.10)$$

Social Disturbance Factor

Social Disturbance is defined as the effects of an event that can alter the structure or normal functioning of a community.

The extent of social unrest is directly dependent on the number of life loss and affected people by an event. For example, the level of unrest experienced by a community would be significantly greater if there are 100 people affected, compared 10 people. Other important parameters that can significantly affect the society are *Displacement, Poverty, Unrest*. The social disturbance resulting from the failure of

a tailings dam is estimated as a weighted sum of those parameters given in Equation (3.11).

$$\text{Social Disturbance} = 0.24(\text{Unrest}) + 0.27(\text{Displacement}) + 0.23(\text{Poverty}) + 0.26 [(\log(\text{PLL} + \text{PLH})/\log(\text{Total Population}))] \quad (3.11)$$

The social *Unrest* resulting from a tailings dam failure is quantified as the weighted sum of scores assigned to factors such as the degree of *Traumatic Stress*, *Loss of cultural entities*, and the *Damage to infrastructure and facilities* (Equation (3.12)).

$$\text{Unrest} = [W_1(\text{Traumatic stress}) + W_2(\text{Loss of cultural entities}) + W_3(\text{Damage to infrastructure and facilities})]/6 \quad (3.12)$$

Where W_i represents the weights assigned to each impact factor, which are derived through expert evaluation or user defined value based on specific social and economic conditions of affected community, and $\sum_{i=1}^3 W_i = 1$.

Table 3.16 Unrest Index

Parameter (Max Score)	Scoring Rubric		
Traumatic stress (Total 6)	Loss of any member of vulnerable groups 3	Loss of any member of community 3	None 0
Damage to Infrastructure (Total 6)	Roads 2	Drinking water or wastewater infrastructure 2	Power or communication lines 2
Loss of cultural entities (6)	Historic or sacred sites 6	Ordinary places of worship or tradition 3	None 0

Traumatic stress resulting from the incident will be quantified based on the number of vulnerable groups affected. Loss of members of vulnerable groups such as children or the elderly, will likely lead to a greater degree of traumatic stress. In addition, the loss of cultural assets can contribute to social unrest. The destruction of places of worship or damage to sacred sites is particularly likely to cause social unrest. Last, damage to infrastructure and essential facilities can also disrupt community's stability. The destruction of roads, contamination of drinking water sources, damage to wastewater systems, and disruption of power or communication

networks will create an environment that is increasingly difficult and uncomfortable for residents. The score of each factor is determined using Table 3.16.

As another social disturbance factor, the potential for displacement resulting from a tailings dam failure is estimated using Equation (3.13), as the weighted sum of scores assigned to factors such as loss of housing, and the loss of public services, forced evacuation where tailings dams are at risk of collapse due to natural flooding or seismic events, the responsible authorities or government may mandate the evacuation of the affected region. Such an evacuation would likely have a significant negative impact on the community, resulting in forced displacement. A high number of collapsed homes may force residents to relocate, while the destruction of critical infrastructure, such as schools or healthcare facilities, may drive further migration as individuals seek access to adequate education and medical services elsewhere.

$$\text{Displacement} = [W_1(\text{Forced evacuation}) + W_2(\text{Loss of houses}) + W_3(\text{Loss of public services})]/6 \quad (3.13)$$

where W_i represent the weights assigned to each impact factor, which are derived through expert evaluation or user defined value dependent to community's specific conditions, and $\sum_{i=1}^3 W_i = 1$.

Table 3.17 Displacement Index

Parameter (Max Score)	Scoring Rubric		
Forced evacuation (Total 6)	Dam site is prone to extreme hydraulic events* 2	Dam site is prone to natural hazards* 2	Dam site is prone to high magnitude earthquakes (> 7) 2
Loss of houses (6)	Proportion of the number of damaged houses to total number of houses > 75 % 6	Proportion of the number of damaged houses to total number of houses $\geq$ 40-75 % 3	Proportion of the number of damaged houses to total number of houses <40 % 1
Loss of public services (6)	Potential damage to school buildings 3	Potential damage to medical service 3	No damage or none 0

* See Table 3.26

Benchmark of *Loss of houses* parameter is determined through expert evaluation. Expert judgement on impact of proportion of lost houses on displacement reveals

that loss of up to 40 % of houses is tolerable by community, whereas in case of loss of 3/4 of houses during the event it is estimated to results in inevitable displacement of community from the site.

The last social disturbance factor, poverty in the community resulting from a tailings dam failure, is assessed based on the loss of livelihoods, loss of ecosystem services, and the disruption of the labour force, as shown in Equation (3.14).

$$\text{Poverty} = W_1(\text{Loss of Livelihoods}) + W_2(\text{Loss of Labor Force}) + W_3(\text{Loss of Ecosystem Services}) \quad (3.14)$$

The loss of livelihoods is estimated by weighted sum of loss of land use, loss of waterbodies and the loss of workplaces (Equation (3.15)).

$$\begin{aligned} \text{Loss of Livelihoods} \\ = W_1(\text{Loss in land use}) + W_2(\text{Loss of water bodies}) \\ + W_3(\text{Loss in workplaces}) \end{aligned} \quad (3.15)$$

where W_i represent the weights assigned to each impact parameter, which are derived through expert evaluation or alternatively assigned by the user according to conditions specific to affected community and its economic life.

Loss of land use is calculated as the ratio of income-generating land lost due to the event to the total available income-generating land (Equation (3.16)). This includes agricultural land, forestry areas, and other productive lands.

$$\text{Loss of land use} = \frac{\text{income generating land lost}}{\text{total income generating land}} \quad (3.16)$$

The loss of water bodies is defined as the ratio of income-generating water bodies that have been polluted as a result of the event to the total number of income-generating water bodies. Examples of such water bodies include groundwater, rivers, wetlands, lakes, and reservoirs (Equation (3.17)).

$$\text{Loss of water bodies} = \frac{(\text{number of lost income generating water bodies})}{(\text{total number of income generating water bodies})} \quad (3.17)$$

The loss of workplaces is defined as the ratio of the number of businesses, factories, workshops, and other main establishments lost due to the event to the total number of main workplaces in the area (Equation (3.18)).

$$\text{Loss of workplaces} = \frac{(\text{number of lost workplaces})}{(\text{total number of workplaces})} \quad (3.18)$$

The loss of the labour force resulting from the incident is estimated by the ratio of the sum of loss of active people, active people lost their health due to event, and unemployment caused by the reduction in available workspaces or employment opportunities to the total labour force in the affected area (Equation (3.19)).

$$\begin{aligned} \text{Loss of Labor Force} \\ &= (\text{APLL} + \text{APLH} + \text{Unemployed People}) \\ &\quad / (\text{Total Number of Labors}) \end{aligned} \quad (3.19)$$

The loss of ecosystem services is the cumulative total of both aquatic and non-aquatic ecosystem services affected (Equation (3.20)). Detailed explanations on determination of values of ecosystem services are given in Section 3.5.3.

$$\begin{aligned} \text{Loss of ecosystem services} \\ &= [W_1 (\text{Aquatic ecosystem services}/8) \\ &\quad + W_2 (\text{Nonaquatic ecosystem services}/8)]/2 \end{aligned} \quad (3.20)$$

where W_1 and W_2 represent the weights assigned to each impact parameter, which are derived through expert evaluation or alternatively assigned by the user according to conditions specific to affected community and its environment, and $W_1 + W_2 = 1$.

Economic Support Factor

Economic Support is defined as financial mechanisms to compensate for damages caused by dam failure. Economic support is expected to be effective in reducing or eliminating *Social Disturbance*.

Economic support for the affected community is estimated by calculating the weighted sum of scores assigned to the likelihood of expected donations, compensation, and available insurance coverage (Equation (3.21)), using the scores

in Table 3.18. Please note that scores are normalized by dividing the maximum score of 2.

$$\text{Economic Support} = \frac{[0.39(\text{Donations}) + 0.38(\text{Compensations}) + 0.23(\text{Insurances})]}{2} \quad (3.21)$$

Table 3.18 Economic Support Index

Parameter (Max Score)	Scoring Rubric		
Donations (Total 2)	Expected donation by NGOs 1	Expected donation by public 1	None 0
Compensations (Total 2)	Expected compensation by mine owner 1	Expected compensation by government 1	None 0
Insurances (2)	Available insurance 2	None 0	

Consequence factor for *Social and Economic Life* is estimated by a function of *Social and Economic Impact* (Equation (3.23)) assuming that it increases exponentially due to inherent nature of social and economic changes and incorporating the indirect changes into account. It is further estimated by a function of *Vulnerability*, *Economic Support*, and *Social Disturbance* (Equation (3.22))

$$\text{Social and Economic Impact} = (\text{Vulnerability} + \text{Social Disturbance}) - 0.55(\text{Economic Support}) \quad (3.22)$$

where $W_s=0.55$ represents the weight derived through expert evaluation, which means that economic support is 55 % effective in reducing social and economic impact caused by the event.

$$\text{Social and Economic Life} = e^{(\text{Social and Economic Impact})} \quad (3.23)$$

3.5.3 Environment

The failure of a tailings dam can have catastrophic environmental consequences. Tailings typically contain heavy metals, chemicals, and other pollutants, and a dam

failure may release this toxic slurry into nearby streams and groundwater sources. Such an event can lead to the death of aquatic life and disrupt entire ecosystems. Additionally, the contamination of land with tailings can make it unsuitable for plant growth, causing long-term damage to the surrounding environment and biodiversity.

Healthy ecosystems provide vital services that benefit human populations. Tailings dam failures can damage these ecosystem functions, reducing the environment's resilience and affecting the well-being of communities that rely on ecosystem services such as clean water, fertile soil, and resources like fish. Furthermore, the failure of a tailings dam can result in the loss of valuable natural areas, including protected regions and recreational areas. The impact on soil and water represents key environmental impacts and *Environmental Impact* is calculated by Equation (3.24).

$$\text{Environmental Impact} = W_1(\text{Impact on Soil}) + W_2(\text{Impact on Water}) \quad (3.24)$$

where W_1 and W_2 represent the weights assigned to each impact factor, which are derived through expert evaluation, and $W_1 + W_2 = 1$.

The impact on soil is estimated based on the proportion of flooded areas (Flood ratio) and the potential risks to soil quality, biodiversity and nonaquatic ecosystem services.

Flood ratio is the proportion of flooded area due to dam failure to total soil covered area of risk the risk body (Equation (3.25))

$$\text{Flood Ratio} = \frac{\text{Flooded Area}}{\text{Total Area}} \quad (3.25)$$

Status of soil quality in potential flooded area is estimated by *Danger to Soil* factor, which is determined based on toxicity of tailings to soil, intensity of contaminants, expected duration of pollution, and ease of clean-up and restoration efforts (see Table 3.19). *Danger to Soil* is calculated by sum of scores assigned to each parameter in Table 3.19.

$$\text{Danger to Soil} = (\text{Toxicity} + \text{Intensity} + \text{Duration} + \text{Restoration})/8 \quad (3.26)$$

It should be noted in Equation (3.26) the sum of scores is normalized dividing the term by the sum of maximum scores (8) in Table 3.19.

Table 3.19 Danger to Soil Index

Parameter (Max Score)	Scoring Rubric	
Toxicity (2)	Tailings is non-toxic to soil 1	Tailings contains toxic substances to soil 2
Intensity (2)	Contaminant source strength is expected to be decreasing significantly within a short time 1	Contaminant source strength is expected to be decreasing within a prolonged time 2
Duration (2)	Pollution is expected to be temporary or short-lasting 1	Pollution is expected to be permanent or long-lasting 2
Restoration (2)	Affected soil can be restored through minor clean-up and restoration efforts 1	Affected soil can be restored through major clean-up and restoration efforts 2

Biodiversity factor is estimated based on the extinction and endemism status of species in the affected area, as well as the protection status of the site. *Biodiversity* is calculated by the sum of scores assigned to each parameter in Table 3.20 (Equation (3.27)).

Table 3.20 Biodiversity Index

Parameter (Max Score)	Scoring Rubric		
Extinction Status (2)	Affected land habituating species in IUCN Red List* under threatened categories (CR, EN, VU) 2	Affected land habituating species in IUCN Red List under other categories (LR, NT, LC) 1	None 0
Endemism Status (2)	Affected lands habituating local endemic species 2	Affected lands habituating regional endemic or widely spread species 1	None 0
Protection Status (2)	Loss of any protected area 2	None 0	

*<https://www.iucnredlist.org>, IUCN: International Union for Conservation of Nature.

$$\text{Biodiversity} = (\text{Extinction Status} + \text{Endemism Status} + \text{Protection Status})/6 \quad (3.27)$$

It should be noted in Equation (3.27) the sum of scores is normalized dividing the term by the sum of maximum scores (6) in Table 3.20.

Besides biodiversity, the failure of a tailings dam significantly impacts the provisions supplied by the affected ecosystem. Land-based ecosystem services are called non-aquatic ecosystem services in this study, and its index is determined based on loss of fertile land, loss of pollination capacity of the site, provided natural products, and loss of its recreational value (Table 3.21).

Non-aquatic ecosystem services factor is calculated by the sum of scores assigned to each parameter in Table 3.21 divided by maximum score (2) in the same table (see Equation (3.28)).

$$\begin{aligned} \text{Non aquatic ecosystem services} \\ = (W_1(\text{Land fertility}) + W_2(\text{Pollination}) + W_3(\text{Natural Products}) \\ + W_4(\text{Recreation}))/2 \end{aligned} \quad (3.28)$$

Where W_i represents the weights assigned to each parameter, and $\sum_{i=1}^4 W_i = 1$. Weights are derived through expert evaluation or defined by the user according to conditions specific to the community and its environment.

Table 3.21 Non-aquatic Ecosystem Services Index

Parameter (Max Score)	Scoring Rubric		
Land fertility (2)	Loss of any income-generating land 2	Loss of ordinary lands 1	None 0
Pollination (2)	Loss of lands covered by vegetation 2	Loss of barren lands 0	
Natural products (2)	Loss of at least two natural products (timber, firewood, mushrooms, herbs, honey, etc.) 2	Loss of any natural products 1	None 0
Recreation (2)	Loss of lands having significant recreational value 2	Loss of lands having any recreational value 1	None 0

After determining the associated factors *Impact on Soil* is calculated by Equation (3.29).

$$\begin{aligned} \text{Impact on Soil} = & (\text{Danger to Soil} \times \text{Flood Ratio}) \\ & \times (\text{Biodiversity} + \text{NonAquatic Ecosystem Services})/2 \end{aligned} \quad (3.29)$$

The impact on water is assessed by evaluating the effects on water bodies within the risk area (Equation (3.33)). These water bodies include surface water sources such as rivers, streams, lakes, wetlands, and reservoirs, as well as groundwater bodies.

Impact on water quality in potential flooded area is estimated by the same approach used to estimate the soil quality. It is estimated by *Danger to Water* factor (Equation 3.30), which is determined based on toxicity of tailings to water body, intensity of contaminants in water, expected duration of pollution, and ease of clean-up and restoration efforts (see Table 3.22).

$$\text{Danger to Water} = (\text{Toxicity} + \text{Intensity} + \text{Duration} + \text{Restoration})/8 \quad (3.30)$$

The sum of scores is normalized dividing the term by total of maximum scores (8) in Table 3.22.

Table 3.22 Danger to Water Index

Parameter (Max Score)	Scoring Rubric	
Toxicity (2)	Tailings is non-toxic to water body 1	Tailings contains toxic substances to water body 2
Intensity (2)	Contaminant source strength is expected to be decreasing significantly within a short time 1	Contaminant source strength is expected to be decreasing within a prolonged time 2
Duration (2)	Pollution is expected to be temporary or short-lasting 1	Pollution is expected to be permanent or long-lasting 2
Restoration (2)	Affected water bodies can be restored through minor clean-up and restoration efforts 1	Affected water bodies can be restored through major clean-up and restoration efforts 2

The impact on aquatic life is determined by considering the presence of species listed on the IUCN Red List, their status of endemism, and loss of ecosystem services after the failure event (see Table 3.23). Aquatic Life factor is calculated by sum of scores assigned to each parameter in Table 3.23 and diving the term dividing the term by the sum of maximum scores (6), as shown in Equation (3.31).

$$\text{Aquatic Life} = (\text{Extinction Status} + \text{Endemism Status} + \text{Protection Status})/6 \quad (3.31)$$

Table 3.23 Aquatic Life Index

Parameter (Max Score)	Scoring Rubric		
Extinction Status (2)	Water bodies habituating species in IUCN Red List under threatened categories (CR, EN, VU) 2	Water bodies habituating species in IUCN Red List under other categories (LR, NT, LC) 1	None 0
Endemism Status (2)	Water bodies habituating local endemic species 2	Water bodies habituating regional endemic or widely spread species 1	None 0
Protection (2)	Affected water body is under protection 2	None 1	

Water bodies can provide important ecosystem services. Drinking water, irrigation water, natural product, and recreation are the aquatic ecosystem services in determining the impact on water. Aquatic ecosystem services is calculated by the sum of scores assigned to each parameter in Table 3.24 divided by the maximum score (2) in the same table (see Equation (3.32)).

$$\begin{aligned} \text{Aquatic ecosystem services} \\ &= [W_1(\text{Drinking Water}) + W_2(\text{Irrigation}) \\ &+ W_3(\text{Aquatic Natural Products}) + W_4(\text{Recreation})]/2 \end{aligned} \quad (3.32)$$

Where W_i represents the weights assigned to each parameter, and $\sum_{i=1}^4 W_i = 1$. Weights are derived through expert evaluation or defined by the user according to conditions specific to the community and its environment.

After determining the associated factors Impact on Water Body is calculated by Equation 3.33.

$$\begin{aligned} \text{Impact on Water Body} \\ &= (\text{Danger to Water}) \\ &\times (\text{Aquatic Life} + \text{Aquatic Ecosystem Services})/2 \end{aligned} \quad (3.33)$$

Table 3.24 Aquatic Ecosystem Services Index

Parameter (Max Score)	Scoring Rubric	
Drinking Water (2)	Water body provides drinking water 2	Water body does not provide drinking water. 1
Irrigation (2)	Lands are irrigated using the water body. 2	Water body does not provide irrigation water. 1
Aquatic Natural Products (2)	Loss of any natural product with an economic importance 2	Loss of any natural product (Fish, reed, etc.) 1
Recreation (2)	Affected water body having significant recreational value 2	Affected water body having any recreational value 1

After determining the Environmental Impact, consequence factor for Environment is calculated by Equation (3.34) assuming that it increases exponentially considering general trend in environmental phenomenon e.g., degradation, growth, and incorporating indirect impacts into account.

$$\text{Environment} = e^{(\text{Environmental Impact})} \quad (3.34)$$

3.5.4 Consequence Classification

Total consequence of a tailings dam failure event is the sum of estimated impacts on Human Health, Social and Economic Life, and Environment given in Equation (3.35).

$$\text{Consequence} = (\text{Human Health}) + (\text{Social and Economic Life}) + (\text{Environment}) \quad (3.35)$$

When associated equations of each impact are inserted in Equation (3.35), it takes the final form as Equation (3.36)

$$\text{Consequence} = \log(\text{PLL} + \text{PLH}) + e^{(\text{Social and Economic Impact})} + e^{(\text{Environmental Impact})} \quad (3.36)$$

Where $\log(\text{PLL} + \text{PLH}) > 0$

It should be noted that when there is no impact on Human Health, that is $PLL + PLH = 0$, Equation (3.36) takes the following form in Equation (3.37)

$$\text{Consequence} = e^{(\text{Social and Economic Impact})} + e^{(\text{Environmental Impact})} \quad (3.37)$$

Social and Economic Impact parameter (SEI) take values between -0.45 and 1.45 whereas values for *Environmental Impact* parameter (EI) ranges between 0 and 1. Lowest limit values and highest limit values imply no expected impact and highest impact, respectively. The benchmark values for consequence classes are determined taking the values 1 and 0.5 for SEI and EI.

The benchmark values of *Human Health* factor (HH) are determined based on similar approach for tailings dam consequence classification of International Commission on Large Dams (ICOLD, 2025). ICOLD classify the potential loss of life (PLL) with benchmark values of 1-10, 10-100, and >100 as “High”, “Very High” and “Extreme”, respectively.

Index values and associated classification of the consequence are given in Table 3.25.

Table 3.25 Consequence Classification (C)

Class	Index Value	Benchmark Value (Upper Limit)	Calculation
Catastrophic	$C \geq 6.33$		
Serious	$5.37 \leq C < 6.37$	HH=100, SEI=1, EI=0.5	$\log 100 + e^1 + e^{0.5}$
Significant	$4.30 \leq C < 5.37$	HH=10, SEI=0.5, EI=1	$\log 10 + e^{0.5} + e^1$
Major	$3.30 \leq C < 4.30$	HH=10, SEI=0.5, EI=0.5	$\log 10 + e^{0.5} + e^{0.5}$
Minor	$C < 3.30$	SEI=0.5, EI=0.5	$e^{0.5} + e^{0.5}$

3.6 Failure Potential Model Parameters

The failure of tailings dams is affected by a variety of causes, with the corresponding patterns and mechanisms exhibiting considerable complexity. Such failures do not typically arise from a single factor but rather result from the interaction of multiple contributing factors. Fundamentally, these failures are influenced by external

environmental factors, such as earthquakes, rainfall, flooding, and subsidence of the dam foundation, which induce changes in the stress and seepage fields, ultimately leading to the destabilization of the structure (Lin et al., 2022).

Failure potential of a tailings dam is estimated by dividing its lifetime in two main stages:

- i. Active life: This period includes the construction, deposition (operation), and closure phases of a tailings dam.
- ii. Inactive life: This period refers to the period following closure (post-closure) or, in the case of abandonment, the post-deposition phase.

Throughout this study tailings dams are categorised and assessed under three distinctive dam types according to stages of their lifetime. Tailings dams in their active lifetime are referred as “Active Dam”. On the other hand, tailings dams in their inactive lifetime are assessed according to their closure phase. If a tailings dam has a certain closure phase during its lifetime, it is denoted as “Closed Dam”. Tailings dams without or unknown closure phase are denoted as “Abandoned Dam”.

Since the factors and parameters are established based on the professional evaluations of experts with experience in the relevant fields, judgements from geotechnical specialists, dam managers, consultants, engineers with experience in tailings dam construction, supervisors or regulators are highly preferable.

The failure potential of a tailings dam is evaluated based on four distinct failure modes:

- i. Overtopping
- ii. Slope instability
- iii. Internal erosion
- iv. Foundation failure

In this study, failure mode of a tailings dam is not a specific mode given above, it is rather an aggregated form of each failure mode along with its root causes given in related tables in following sections.

The failure potential of a tailings dam is influenced not only by its vulnerability to various failure modes but also by management factors throughout its operational lifespan (active life) and after its closure (inactive life). Furthermore, management practices play a critical role at every stage of the dam's life cycle, from design through to post closure. In other words, the potential for failure is assessed through a comprehensive evaluation of failure modes, and the associated management practices.

3.6.1 Active Dam Failure Potential

Failure potential of an active dam is determined by its failure mode causing the dam to fail, and its management factor which reduces the failure potential.

Failure Mode of Active Dam

It is assessed using Equation (3.38), a weighted sum of scores based on individual failure modes, that are overtopping, slope instability, internal erosion, and foundation.

$$\begin{aligned} \text{Active Dam Failure Mode} \\ &= 0.21(\text{Overtopping}) + 0.31(\text{Slope Instability}) \\ &+ 0.20(\text{Internal Erosion}) + 0.28(\text{Foundation Failure}) \end{aligned} \quad (3.38)$$

i) Overtopping: Its score is estimated using Equation (3.39), a weighted sum of scores assigned to extreme hydraulic events, natural hazards, excess water storage, flood control facilities, spillway and free board (Table 3.26).

Overtopping Mode

$$= [0.18(\text{Extreme hydraulic events}) + 0.21(\text{Natural hazards}) + 0.20(\text{Excess Water Storage}) + 0.21(\text{Flood control facilities or spillway and freeboard}) + 0.20(\text{Dam type})]/6 \quad (3.39)$$

Table 3.26 Overtopping Mode Index

Parameter (Max Score)	Scoring Rubric			
Extreme hydraulic events (Total 6)	Site is prone to high intensity or tropical rainfall 2	Site is prone to high snowmelt 2	Site is prone to hurricanes 2	
Natural hazards (Total 6)	Site is prone to landslide 2	Site is prone to avalanche 2	Site is prone to tornado or extreme winds 2	
Excess water storage (6)	None 6	Available volume < ½PMF 4	Available volume for ½PMF to PMF 2	Available volume for both PMF and PMP 1
*Flood control facilities (6)	No constructed diversion channel or dike 6	As-built with ≤Q ₁₀₀ criteria or unknown 4	As-built with >Q ₁₀₀ criteria 2	As-built with ≥ Q ₁₀₀₀ criteria 1
**Spillway and free board (6)	No spillway 6	Spillway with less than 1 m free board 3	Spillway with at least 1 m free board 1	
Dam type (6)	Multi stage (raised) 6	Single stage or water-retention 2		

* For raised or multi-stage dams

** For single-stage or water retention type dams

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

Extreme precipitation events (rainstorms, rapid snowmelt) lead to a substantial and rapid increase in the volume of water flowing into the tailings dam. If the dam's spillway or flood control systems are not designed or operated to handle these peak flows, the water level in the pond can rise quickly, reducing the freeboard (the vertical distance between the water level and the crest of the dam).

ii) Slope Instability: Its score is estimated by Equation (3.40), a weighted sum of scores given to the seismicity of the region, type of construction material used, available drainage and seepage facilities, location of the phreatic surface in the dam,

height and inclination of the slope of dam, erosion on dam wall, and dam type Table 3.27.

Slope Instability Mode

$$= [0.13(\text{Seismicity}) + 0.14(\text{Construction material}) + 0.12(\text{Seepage facilities}) + 0.11(\text{Drainage facilities}) + 0.10(\text{Phreatic surface}) + 0.14(\text{Height and inclination}) + 0.13(\text{Erosion}) + 0.13(\text{Dam type})]/6 \quad (3.40)$$

Table 3.27 Slope Instability Mode Index

Parameter (Max Score)	Scoring Rubric			
Seismicity (6)	PGA > 0.20g without design 6	PGA > 0.20g with proper design* 4	PGA < 0.20g without design 4	PGA < 0.20g with proper design* 2
Construction material (6)	Tailings 6	Earth fill (Sand, slime, clay) 4	Compacted earth fill 2	Rock fill 1
Seepage facilities (6)	None 6	Active facilities (pumping) 3	Passive facilities (liners or cores) 1	
Drainage facilities (6)	None 6	Active facilities (decanting) 3	Passive facilities (drains) 1	
Phreatic surface (6)	No control or monitoring 6	Passive control (internal zoning or drains) without monitoring 4	Passive control with monitoring 2	Seepage facility with monitoring 1
Height and inclination (6)	≥30 m and >27° 6	≥10 m and >27° 4	≤27° 2	<18° 1
Erosion (Total 6)	Site is prone to extreme weather conditions 2	Dam is constructed with soft soil or tailings itself 2	Dam wall face without protective cover 2	
Dam type (6)	Upstream 6	Centerline 4	Downstream 3	Single stage or water-retention 1

* 475-yr return period and <1% exceedance

PGA: Peak Ground Acceleration

Earthquakes are a major factor that can trigger the failure of tailings dams, particularly those constructed with susceptible materials (e.g., loose, saturated, fine-grained tailings) or using less stable construction methods (like the upstream method). Earthquakes generate dynamic (cyclic) loading on the saturated tailings material creating cyclic softening and liquefaction.

The phreatic surface, which is the boundary between the saturated and unsaturated zones within a tailings dam, significantly impacts its slope instability. Below the phreatic surface, the pores within the tailings material are fully saturated with water exerting pore water pressure. As the phreatic surface rises, the saturated zone expands, increasing pore water pressure over a larger volume of the dam which decreases the shear strength. A lower shear strength makes the slope more susceptible to sliding.

The height and inclination (steepness) of a tailings dam slope directly impact its stability by influencing the balance between the forces trying to cause a slide and the forces resisting it. Increasing the height or the inclination of a tailings dam slope both work to increase the driving forces and decrease the resisting forces, thereby reducing the factor of safety and making the dam more prone to slope instability and failure.

External erosion is another factor decreasing stability of a tailings dam. Surface erosion from rainfall and wind can degrade the dam face and potentially expose weaker underlying material, initiating or worsening instability.

iii) Internal Erosion: Internal erosion, often called "piping," severely impacts tailings dam stability. It gradually hollows out and weakens the dam from inside, making it highly susceptible to sudden and complete failure, often without obvious external signs.

Water seeping through the dam dislodges and carries away fine particles within the dam's body. This creates voids and channels (pipes) within the embankment. As material is removed, the dam's cross-section is weakened, reducing its effective mass and the interlocking of particles that provides shear strength. The formation of pipes provides preferential pathways for water flow, leading to increased seepage velocities. This can accelerate further erosion and lead to higher, more concentrated pore water pressures within the dam. If these pipes grow large enough and connect to the dam's external faces, they can lead to a sudden and catastrophic collapse as a section of the dam loses all support and washes out.

It is evaluated using Equation (3.41), a weighted sum of scores for available seepage facilities, type of construction material used, location of the phreatic surface, width of dry beach, and dam type (Table 3.28).

$$\text{Internal Erosion Mode} = [0.20(\text{Seepage control}) + 0.20(\text{Construction material}) + 0.20(\text{Phreatic surface}) + 0.17(\text{Dry beach width}) + 0.23(\text{Dam type})]/6 \quad (3.41)$$

Table 3.28 Internal Erosion Mode Index

Parameter (Max Score)	Scoring Rubric			
Seepage control (6)	None 6	Active facilities (pumping) 3	Passive facilities (liners or cores) 1	
Construction material (6)	Tailings 6	Earth fill (Sand, slime, clay) 4	Compacted earth fill 2	Rock fill 1
Phreatic surface (6)	No control or monitoring 6	Passive control (internal zoning or drains) without monitoring 4	Passive control with monitoring 2	Seepage facility with monitoring 1
Dry beach location and width (6)	Beach is against dam (facing) 6	Length of beach (L)/Height of dam (H) < 5 4	L/H>5 2	L/H>9 1
Dam type (6)	Upstream 6	Downstream or centerline 4	Single-stage 3	water-retention 1

Seepage control systems manage water flow within the dam to ensure that water pressures remain low and that no material is washed out, thereby directly preventing the initiation and progression of internal erosion. The dry beach in a tailings dam is the exposed, drier area of coarser tailings particles that forms between the point of discharge and the supernatant (water) pond. Its location and width are critical for preventing internal erosion. A wide and stable dry beach acts as a critical natural barrier, maintaining a safe distance between the water pond and the dam structure, controlling seepage, and creating a less erodible zone, all of which are vital for preventing internal erosion. Type of construction material and how different materials are zoned and filtered within the dam structure are paramount. Materials that are highly erodible or that create large contrasts in permeability when placed next to other materials, without proper filter design, drastically increase the risk of internal erosion and subsequent dam failure.

iv) Foundation Failure: It is assessed using Equation (3.42), a weighted sum of scores based on factors such as available drainage and seepage facilities, foundation properties, groundwater condition, and the seismicity of the region, subsidence potential of site, and dam type (Table 3.29).

$$\begin{aligned} \text{Foundation Failure} &= [0.13(\text{Drainage facilities}) + 0.12(\text{Seepage control}) \\ &+ 0.16(\text{Foundation properties}) + 0.15(\text{Groundwater condition}) \\ &+ 0.15(\text{Seismicity}) + 0.15(\text{Subsidence}) + 0.14(\text{Dam type})]/6 \end{aligned} \quad (3.42)$$

Table 3.29 Foundation Mode Index

Parameter (Max Score)	Scoring Rubric			
Seepage control (6)	None 6	Active facilities (pumping) 3	Passive facilities (liners) 1	
Drainage facilities (6)	None 6	Active facilities (decanting) 3	Passive facilities (drains) 1	
Foundation properties (6)	Weak and soft soils 6	Cracked or fractured rocks 4	Mixed material 4	Massive rock 1
Groundwater condition (6)	Sited on saturated zone 6	Sited on shallow unsaturated zone 3	Sited on thick unsaturated zone 1	
Seismicity (6)	PGA > 0.20g without design 6	PGA > 0.20g with proper design* 4	PGA < 0.20g without design 4	PGA < 0.20g with proper design* 2
Subsidence (6)	Sited on an underground mine or karst caverns 6	Sited on geological formations prone to volume change (compressible or swelling clays, soluble salts etc.) 4	Sited on geological formations prone to weakness (faults and shear zones, unconsolidated sediments etc.) 4	None 0
Dam type (6)	Upstream 6	Centerline 4	Single stage Downstream 3	Water-retention 1

* 475-yr return period and <1% exceedance

Seepage control and drainage facilities are paramount in preventing foundation failure of a tailings dam by managing water flow and pressure beneath and around the dam. Robust seepage control and drainage facilities are critical to maintaining the stability of a tailings dam's foundation by managing water pressures, preserving the shear strength of foundation materials, and preventing erosional processes that

could undermine the dam. Foundation properties significantly influence the risk of tailings dam failure because the dam transfers its entire weight and impoundment forces to the underlying ground. The foundation must be strong enough to support the dam's weight, stable enough to resist deformation, and permeable enough to manage pore water pressures without allowing erosion. Inadequate foundation properties can lead to a cascade of failure mechanisms, from simple sliding to catastrophic liquefaction. Groundwater conditions are another critical factor in tailings dam foundation failure, primarily by influencing the pore water pressure within the foundation soils. A high groundwater table and uncontrolled groundwater flow significantly increase the susceptibility of a tailings dam's foundation to failure by reducing its strength, promoting erosion, and creating conditions for liquefaction. Additionally, any underlying geological feature or man-made opening that can lead to a loss of ground support or significant, uneven volume change creates a direct and often unpredictable threat to the structural integrity and stability of a tailings dam's foundation.

Management Factor

Management Factor is defined as the combination of human activities such as operation, monitoring, supervision, etc. to prevent the failure of a tailings dam.

Management factor during active life of a tailings dam is evaluated under three sub-management factors:

- (i) Dam Safety Management
- (ii) Internal Management
- (iii) External Management

Management factor of an active dam is estimated by the weighted sum of sub-factors, as given in Equation (3.43).

$$\text{Management factor} = 0.36(\text{Dam Safety Management}) + 0.34(\text{Internal Management}) + 0.30(\text{External Management}) \quad (3.43)$$

Safety Management is assessed using Equation (3.44), a weighted sum of dam safety monitoring, warning system, emergency planning, training and safety culture of workers, supervision and responsibility (Table 3.30).

$$\begin{aligned} \text{Dam safety management factor} &= [0.22(\text{Dam safety monitoring}) + 0.21(\text{Warning system}) \\ &+ 0.18(\text{Emergency planning}) \\ &+ 0.19(\text{Training and safety culture of workers}) \\ &+ 0.20(\text{Supervision and responsibility})]/6 \end{aligned} \quad (3.44)$$

Table 3.30 Dam Safety Management Factor Index

Parameter (Max Score)		Scoring Rubric		
Dam safety monitoring (6)	Seismic activity	Monitoring phreatic surface and seepage	Monitoring water level in the dam	Dam movement
	1	2	1	2
Warning system (6)	Established online warning system	Any means of warning system	None	
	6	3	0	
Emergency planning (6)	Emergency planning in action	Only documented emergency plans	None	
	6	3	0	
Training and safety culture of workers (6)	Ongoing training and follow-up of protocols	Only informative documents or guidelines	None	
	6	3	0	
Supervision and responsibility (6)	Appointed an accountable executive for dam	Responsible site person	Engineer of record	Technical reviewer
	1	2	2	1

Internal Management is assessed using Equation (3.45), a weighted sum of design construction practices, qualification and experience of involved parties, and maintenance practices during construction and operation (Table 3.31).

$$\text{Internal management factor} = [0.34(\text{Design and construction}) + 0.35(\text{Qualification and Experience}) + 0.31(\text{Maintenance practices})]/6 \quad (3.45)$$

External Management is evaluated using Equation (3.46), a weighted sum of external audit, external monitoring, regulatory control (Table 3.32).

$$\text{External management factor} = [0.34(\text{External Audit}) + 0.33(\text{External monitoring}) + 0.33(\text{Regulatory control})]/6 \quad (3.46)$$

where W_i represent the weights assigned to each impact factor, which are derived through expert evaluation, and $\sum_{i=1}^3 W_i = 1$.

Table 3.31 Internal Management Factor Index

Parameter (Max Score)	Scoring Rubric		
Design and construction (6)	Construction with proper design 6	Construction with any design 3	Construction without design 0
Qualification and Experience (Total 6)	Qualified and experienced consultant 2	Qualified and experienced contractor 2	Qualified and experienced operator 2
Maintenance practices (6)	Incident during construction 3*	Incident during operation 3*	

* Score is determined by subtracting from maximum score (if both are valid then score is 0)

Table 3.32 External Management Factor Index

Parameter (Max Score)	Scoring Rubric			
External Audit (6)	Systematic audit or technical review 6	Any audit or review 3	None 0	
External monitoring (6)	Established monitoring system 6	Monitoring on request 3	None 0	
Regulatory control (6)	Regular control 6	Irregular control 3	None 0	

Failure potential of active tailings dam is assessed using Equation (3.47) and assuming it increases exponentially.

$$\text{Active Dam Failure Potential} = e^{1+(\text{Failure Mode})-0.77(\text{Management Factor})} \quad (3.47)$$

where $W_m = 0.77$ is the active dam management ratio and it represent the weights assigned to management factor, which is derived through expert evaluation.

3.6.2 Closed Dam Failure Potential

Since a tailings dam is a permanent structure in the mine, it has a potential of failure after closure stage (post-closure). Overtopping, slope instability, internal erosion, and foundation failure are identified as the four failure modes, each with distinct indices, in the evaluation of the failure potential of closed dams. The failure potential for each case is assessed through a combination of relevant management factors and failure modes.

Failure Mode of Closed Dam

Failure mode of closed dam is assessed using Equation (3.48), a weighted sum of scores based on individual failure modes, that are overtopping, slope instability, internal erosion, and foundation failure. Weights of each failure mode is determined through expert evaluation.

$$\begin{aligned} \text{Closed Dam Failure Mode} \\ = 0.20(\text{Overtopping}) + 0.32(\text{Slope Instability}) \\ + 0.21(\text{Internal Erosion}) + 0.27(\text{Foundation Failure}) \end{aligned} \quad (3.48)$$

As indicated by the weights in Equation (3.48), slope instability is the most significant failure mode in the closed dam failure mode. Foundation failure appears to be the second most influential, while overtopping and internal erosion are the least significant failure modes.

i) Closed Dam Overtopping: It is estimated using Equation (3.49), a weighted sum of scores given to the extreme hydraulic events, natural hazards, excess water storage, flood control facilities, spillway and free board (Table 3.33).

$$\text{Closed Dam Overtopping Mode} = [0.31(\text{Extreme hydraulic events}) + 0.34(\text{Natural hazards}) + 0.35(\text{Flood control facilities})]/6 \quad (3.49)$$

Table 3.33 Closed Dam Overtopping Mode Index

Parameter (Max Score)	Scoring Rubric			
Extreme hydraulic events (Total 6)	Site is prone to high intensity or tropical rains 2	Site is prone to high snowmelt 2	Site is prone to hurricanes 2	
Natural hazards (Total 6)	Site is prone to landslide 2	Site is prone to avalanche 2	Site is prone to tornados or extreme winds 2	
*Flood control facilities and excess water storage (6)	As-built with <Q ₁₀₀₀₀ criteria and available storage volume for at least 1/3 PMF 6	As-built with <Q ₁₀₀₀₀ criteria and available volume for PMF 4	As-built with Q ₁₀₀₀₀ criteria and available volume for at least 1/3 PMF 3	As-built with Q _{catastrophic} 1
*Flood control facilities and spillway (6)	As-built with <Q ₁₀₀₀₀ criteria and spillway with less than 1 m free board 6	As-built with <Q ₁₀₀₀₀ criteria and spillway with at least 1 m free board 4	As-built with ≥Q ₁₀₀₀₀ criteria and spillway with less than 1 m free board 2	As-built with ≥Q ₁₀₀₀₀ criteria and spillway with at least 1 m free board 1

* Appropriate design should be selected and rated

PMF: Probable Maximum Flood (72-hr)

ii) Closed Dam Slope Instability: Its score is estimated by Equation (3.50), a weighted sum of scores given to the seismicity of the region, seepage and drainage measures, height and inclination of the slope of dam, erosion measures (Table 3.34).

$$\begin{aligned} \text{Closed Dam Slope Instability Mode} \\ = & [0.17(\text{Seismicity}) + 0.19(\text{Construction material}) \\ & + 0.15(\text{Seepage and drainage measures}) \\ & + 0.16(\text{Height and inclination}) + 0.16(\text{Erosion measures}) \\ & + 0.17(\text{Dam type})]/6 \end{aligned} \quad (3.50)$$

iii) Closed Dam Internal Erosion: It score is evaluated using Equation (3.51), a weighted sum of scores based on factors such as available seepage and drainage measures, type of construction material used, phreatic surface control (Table 3.35).

$$\begin{aligned} \text{Closed Dam Internal Erosion Mode} \\ = & [0.24(\text{Seepage and drainage facilities}) \\ & + 0.27(\text{Construction material}) + 0.24(\text{Phreatic surface control}) \\ & + 0.25(\text{Dam type})]/6 \end{aligned} \quad (3.51)$$

Table 3.34 Closed Dam Slope Instability Index

Parameter (Max Score)	Scoring Rubric			
Seismicity design (6)	PGA > 0.20g and designed with <2475-yr return period 6	PGA > 0.20g and designed with >2475-yr return period 4	PGA ≤ 0.20g and designed with <2475-yr return period 4	PGA ≤ 0.20g and designed with >2475-yr return period 2
Seepage and drainage measures (6)	None 6	liner or core without base drainage with impervious top- cover 4	liner or core with base drainage without impervious top- cover 3	liner or core with drainage and impervious top- cover 1
Construction material (6)	Tailings 6	Earth fill (Sand, slime, clay) 4	Compacted earth fill 2	Rock fill 1
Height and inclination (6)	>30 m and >27° 6	>10 m and >27° 4	≤27° 2	<18° 1
Erosion measures (6)	Dam is constructed with soft soil or tailings itself without cover 6	Dam is constructed with compacted earth fill or rock fill without cover 4	Dam walls are covered with any protective material 2	Dam walls are covered with rip- rap material or vegetation 1
Dam type (6)	Upstream 6	Centerline 4	Downstream 3	Single stage or water-retention 1

Table 3.35 Closed Dam Internal Erosion Index

Parameter (Max Score)	Scoring Rubric			
Seepage and drainage measures (6)	None 6	liner or core without base drainage with impervious top-cover 4	liner or core with base drainage without impervious top-cover 3	liner or core with drainage and impervious top-cover 1
Construction material (6)	Tailings 6	Earth fill (Sand, slime, clay) 4	Compacted earth fill 2	Rock fill 1
Phreatic surface control (6)	No control measures 6	Passive control (internal zoning or drains) 4	Seepage measure without impervious top-cover 2	Dewatered with impervious top-cover 1
Dam type (6)	Upstream 6	Centerline 4	Downstream or single stage 3	Water-retention 1

iv) Closed Dam Foundation Failure: It is assessed using Equation (3.52), a weighted sum of scores based on factors such as applied seepage measures, foundation properties, groundwater condition, the seismicity of the region and applied measures, and subsidence measures (Table 3.36).

Closed Dam Foundation Failure

$$= [0.16(\text{Seepage measures}) + 0.20(\text{Foundation properties}) + 0.16(\text{Groundwater condition}) + 0.17(\text{Seismicity measure}) + 0.16(\text{Subsidence measure}) + 0.15(\text{Dam type})]/6 \quad (3.52)$$

Table 3.36 Closed Dam Foundation Failure Index

Parameter (Max Score)	Scoring Rubric			
Seepage measures (6)	None 6	Drains, blankets etc. 4	Liners 2	
Foundation properties (6)	Weak and soft soils 6	Cracked or fractured rocks 3	Massive rock 1	
Groundwater condition (6)	Sited on saturated zone 6	Sited on shallow unsaturated zone 3	Sited on thick unsaturated zone 1	
Seismicity measure (6)	PGA > 0.25g 6	PGA > 0.25g with measures 4	PGA < 0.25g 2	PGA < 0.25g with measures 1
Subsidence measure (6)	Sited on an underground mine or opening without measure 6	Sited on an underground mine or opening with measure 3	Sited on karstic formation 4	None 0
Dam type (6)	Upstream 6	Centerline 4	Downstream or single stage 3	Water-retention 1

Post Closure Management Factors

In addition to the failure mode factors, management factors are also of great importance during inactive life of a tailings dam. Post-closure factors like supervision, monitoring and warning system, regulatory control, closure planning, capital investment affects the safe deposition of the tailings dam.

The post-closure management factor is assessed using Equation (3.53), a weighted sum of supervision, monitoring and warning system, regulatory control, closure planning, capital investment Table 3.37.

$$\begin{aligned} \text{Post Closure Management Factor} \\ = [0.19(\text{Supervision}) + 0.20(\text{Monitoring and warning system}) \\ + 0.19(\text{Regulatory control}) + 0.22(\text{Closure planning}) \\ + 0.20(\text{Capital investment})]/6 \end{aligned} \quad (3.53)$$

Table 3.37 Post-closure Management Factor Index

Parameter (Max Score)	Scoring Rubric		
Supervision (6)	Systematic audit 6	Any audit 3	None 0
Monitoring and warning system (6)	Established monitoring system 6	Monitoring on request 3	None 0
Regulatory control at closure (6)	Periodic control by relevant authorities 6	Irregular or on-requested control 3	None 0
Closure planning (Total 6)	Life-time planning 2	Approved closure plan 2	Technical review 2
Capital investment (Total 6)	Pre-capital investment for closure 2	Available financial instruments for closure activities 2	Available financial instruments for future repair or maintenance 2

After determination of closed dam failure mode and post-closure management factor, failure potential of a closed tailings dam is assessed using Equation (3.54).

$$\begin{aligned} \text{Closed Dam Failure Potential} \\ = e^{1+\text{Closed Dam Failure Mode}-0.70(\text{Post Closure Management Factor})} \end{aligned} \quad (3.54)$$

where $W_c = 0.70$ is the closed dam management ratio and it represents the weight assigned to management factor, which is derived through expert evaluation.

3.6.3 Abandoned Dam Failure Potential

Abandoned dams are closed without or limited closure activity. Abandoned dams also differ from closed dams with limited information and data about their active lifetime.

Failure Mode of Abandoned Dam

It is assessed using Equation (3.55), a weighted sum of scores based on individual failure modes, that are overtopping, slope instability, internal erosion, and foundation failure.

$$\begin{aligned} \text{Abandoned Dam Failure Mode} \\ &= 0.19(\text{Overtopping}) + 0.33(\text{Slope Instability}) \\ &+ 0.21(\text{Internal Erosion}) + 0.27(\text{Foundation Failure}) \end{aligned} \quad (3.55)$$

As the weights in Equation (3.55) indicate, the most effective failure mode is the slope instability in closed dam failure mode. Foundation failure is seemed to be the second effective. Overtopping and internal erosion approximate each other and they are the least effective failure modes.

i) Abandoned Dam Overtopping: Overtopping Mode causing the failure of an abandoned tailings dam, is estimated using Equation (3.56), a weighted sum of scores given to the extreme hydraulic events, natural hazards, flood control measures (Table 3.38).

$$\begin{aligned} \text{Abandoned Dam Overtopping Mode} \\ &= [0.33(\text{Extreme hydraulic events}) + 0.35(\text{Natural hazards}) \\ &+ 0.32(\text{Flood control measures})]/6 \end{aligned} \quad (3.56)$$

Table 3.38 Abandoned Dam Overtopping Mode Index

Parameter (Max Score)	Scoring Rubric			
Extreme hydraulic events (6)	Site is prone to high intensity or tropical rains 2	Site is prone to high snowmelt 2	Site is prone to hurricanes 2	
Natural hazards (6)	Site is prone to landslide 2	Site is prone to avalanche 2	Site is prone to tornados or extreme winds 2	
Flood control measures (6)	None 6	Diversion channels or dikes with unknown design 4	Spillway with unknown design 4	Flood control measures with closure design 3 or 2*

* Rated according to design

ii) Abandoned Dam Slope Instability: Its value is estimated by Equation (3.57), a weighted sum of scores given to seismicity design, seepage and drainage measures, height and inclination of the slope of dam, erosion measures (Table 3.39).

$$\begin{aligned}
 &\text{Abandoned Dam Slope Instability Mode} \\
 &= [0.17(\text{Seismicity}) + 0.19(\text{Construction material}) \\
 &\quad + 0.14(\text{Seepage and drainage measures}) \\
 &\quad + 0.17(\text{Height and inclination}) + 0.16(\text{Erosion measures}) \\
 &\quad + 0.17(\text{Dam type})]/6
 \end{aligned} \tag{3.57}$$

iii) Abandoned Dam Internal Erosion: It is evaluated using Equation (3.58), a weighted sum of scores based on factors such as available seepage and drainage measures, type of construction material used, phreatic surface control (Table 3.40).

$$\begin{aligned}
 &\text{Abandoned Dam Internal Erosion Mode} \\
 &= [0.24(\text{Seepage and drainage measures}) \\
 &\quad + 0.26(\text{Construction material}) + 0.25(\text{Phreatic surface control}) \\
 &\quad + 0.25(\text{Dam type})]/6
 \end{aligned} \tag{3.58}$$

Table 3.39 Abandoned Dam Slope Instability Mode Index

Parameter (Max Score)	Scoring Rubric			
Seismicity design (6)	PGA $\geq$ 0.20g with unknown closure design 6	PGA $\geq$ 0.20g with closure design 5 or 4*	PGA < 0.20g with unknown closure design 4	PGA < 0.20g with any design 4 to 2*
Seepage and drainage measures (6)	None or sign of seepage 6	Unknown 5	Measures with unknown design 4	Measures with any design 3 or 2*
Construction material (6)	Tailings or unknown 6	Earth fill or mixed fill 4	Compacted fill 3	Rock fill 2
Height and inclination (6)	>30 m and >27° 6	10 to 30 m and >27° 4	$\leq$ 27° 2	<18° 1
Erosion measures (6)	Dam is constructed with unknown fill or tailings itself without cover 6	Dam is constructed with compacted fill without cover 4	Dam walls are covered with any protective cover 3	Dam walls are covered with rip-rap material or vegetation 2
Dam type (6)	Upstream 6	Centerline 4	Downstream or single stage 3	Water-retention 1

* Rated according to measure or design

Table 3.40 Abandoned Dam Internal Erosion Mode Index

Parameter (Max Score)	Scoring Rubric			
Seepage and drainage measures (6)	None or sign of seepage 6	Unknown 5	Measures with unknown design 4	Measures with any design 4 to 2*
Construction material (6)	Tailings or unknown 6	Earth fill or mixed fill 4	Compacted fill 3	Rock fill 2
Phreatic surface control measures (6)	No control measures 6	Passive control without top-cover (internal zoning or drains) 4	Seepage measure with pervious top-cover 4 or 3*	Seepage measure with impervious top-cover 2
Dam type (6)	Upstream 6	Centerline 4	Downstream or single stage 3	Water-retention 1

* Rated according to measure or design

iv) Abandoned Dam Foundation Failure: It is assessed using Equation (3.59), a weighted sum of scores based on factors such as applied seepage measures, foundation properties, groundwater condition, the seismicity measures, and subsidence measures (Table 3.41).

$$\begin{aligned} \text{Abandoned Dam Foundation Failure Mode} \\ = & [0.15(\text{Seepage measures}) + 0.19(\text{Foundation properties}) \\ & + 0.16(\text{Groundwater condition}) + 0.18(\text{Seismicity measure}) \\ & + 0.16(\text{Subsidence measure}) + 0.16(\text{Dam type})]/6 \end{aligned} \quad (3.59)$$

Abandoned Dam Management Factor

If a tailings dam is abandoned its operator is no longer on site, that means only public or relevant authorities could manage the tailings dam. Management factor of an abandoned tailings dam is assessed using Equation (3.60), with scores listed in (Table 3.42).

$$\begin{aligned} \text{Abandoned Dam Management Factor} \\ = & [0.34(\text{Monitoring and warning system}) \\ & + 0.32(\text{Regulatory control}) + 0.34(\text{Dam behaviour})]/6 \end{aligned} \quad (3.60)$$

Table 3.41 Abandoned Dam Foundation Failure Mode Index

Parameter (Max Score)	Scoring Rubric			
Seepage measures (6)	None 6	Unknown 5	Measures with unknown design 4	Measures with any design 4 to 2*
Foundation properties (6)	Weak and/or soft soils 6	Unknown 5	Cracked or fractured rocks 3	Massive rock 1
Groundwater condition (6)	Sited on saturated zone 6	Unknown 5	Sited on shallow unsaturated zone 3	Sited on thick unsaturated zone 1
Seismicity measure (6)	PGA > 0.20g 6	PGA > 0.20g with measures or unknown 4	PGA < 0.20g 2	PGA < 0.20g with measures 1
Subsidence measure (6)	Sited on an underground mine or opening without measure 6	Sited on an underground mine or opening with measure 3	Sited on karstic formation or unknown 4	None 0
Dam type (6)	Upstream 6	Centerline 4	Downstream or single stage 3	Water-retention 1

Table 3.42 Abandoned Dam Management Factor Index

Parameter (Max Score)	Scoring Rubric		
Monitoring and warning system (6)	Established monitoring system 6	Monitoring on request 3	None 0
Regulatory control (6)	Periodic control by relevant authorities 6	Irregular or on-requested control 3	None 0
Dam behavior (6)	None 6	Dam had any incident that required technical inspection 3	Dam had any incident that required maintenance 0

After determining failure mode and management factor of abandoned dam, failure potential of an abandoned tailings dam is assessed using Equation (3.61).

$$\text{Abandoned Dam Failure Potential} = e^{1+(\text{Abandoned Dam Failure Mode})-0.66(\text{Abandoned Dam Management Factor})} \quad (3.61)$$

where $W_a = 0.66$ is the management ratio and it represents the weight assigned to management factor, which is derived through expert evaluation.

3.6.4 Failure Potential Classification

Failure potential of a tailings dam is determined by two main factors of failure mode and management, and additionally the management ratio. General form of failure potential calculation is given in Equation (3.62). The values of management ratio differ according to dam status being active (0.77), closed (0.70) or abandoned (0.66). Since failure mode and management factor take values between 0 and 1, minimum value of failure potential is 1.26 (in case of active dam) whereas its maximum value is 7.39.

$$\text{Failure Potential} = e^{1+(\text{Failure Mode})-(\text{Management Ratio})(\text{Management Factor})} \quad (3.62)$$

Failure potential of a tailings dam is classified into five classes using bench mark values of 0, 0.5, and 1. The classification is based on active dam status, because it has the highest management ratio so that it gives lowest limit value with a

conservative approach. Index values and associated classification of the failure potential are given in Table 3.43.

Table 3.43 Failure Potential Classification (FP)

Class	Index Value	Benchmark Value (Upper limit)	Calculation (e ^x)
Extreme	$FP \geq 5.03$		
Very High	$3.42 \leq FP < 5.03$	FM=1, MF=0.5	$1+1-(0.77) (0.5)$
High	$2.72 \leq FP < 3.42$	FM=1, MF=1	$1+1-(0.77) (1)$
Significant	$1.85 \leq FP < 2.72$	FM=0, MF=0	$1+0-(0.77) (0)$
Low	$FP < 1.85$	FM=0, MF=0.5	$1+0-(0.77) (0.5)$

The "low" class in this classification refers to a tailings dam that is equipped with all the necessary conditions for safe production. If a tailings dam meets the basic conditions but require managerial assistant it is classified as "significant". The dams having problems and requiring treatment are under "high" failure potential, "very high" failure potential class includes the dams having hidden serious problems, if not timely treatment will lead to tailings dam break. The tailings dam in "extreme" potential class breaks at any time.

3.7 Risk Classification

Risk is determined by product of consequence of the failure event and its failure potential (Equation (3.62)). The risk is classified under five categories given in Value of risk classes are determined as products of respected bench marks of consequence classes (C) and failure potential classes (FP). For example, upper limit of "Negligible" class (6.11) is the product of upper limits of "Minor" consequence class (3.30) and "Low" failure potential class (1.85). In same manner, upper limit of "Serious" class is the product of upper limits of "Serious" consequence class and "Very High" failure potential class. Risk classes are given in Table 3.44 and their representation is shown in Figure 3.2.

$$\text{Risk} = (\text{Consequence}) \times (\text{Failure Potential}) \quad (3.63)$$

Value of risk classes are determined as products of respected bench marks of consequence classes (C) and failure potential classes (FP). For example, upper limit of “Negligible” class (6.11) is the product of upper limits of “Minor” consequence class (3.30) and “Low” failure potential class (1.85). In same manner, upper limit of “Serious” class is the product of upper limits of “Serious” consequence class and “Very High” failure potential class. Representation of risk classes are shown in Figure 3.2.

Table 3.44 Risk Classification (R)

Class	Index Value	Benchmark value (Upper limit)
Extreme	$R \geq 32.04$	
Serious	$18.37 \leq R < 32.04$	FP=5.03 (Very High), C=6.37 (Serious)
High	$11.70 \leq R < 18.37$	FP=3.42 (High), C=5.37 (Significant)
Significant	$6.11 \leq R < 11.70$	FP=2.72 (Significant), C=4.30 (Major)
Negligible	$R < 6.11$	FP=1.85 (Low), C=3.30 (Minor)

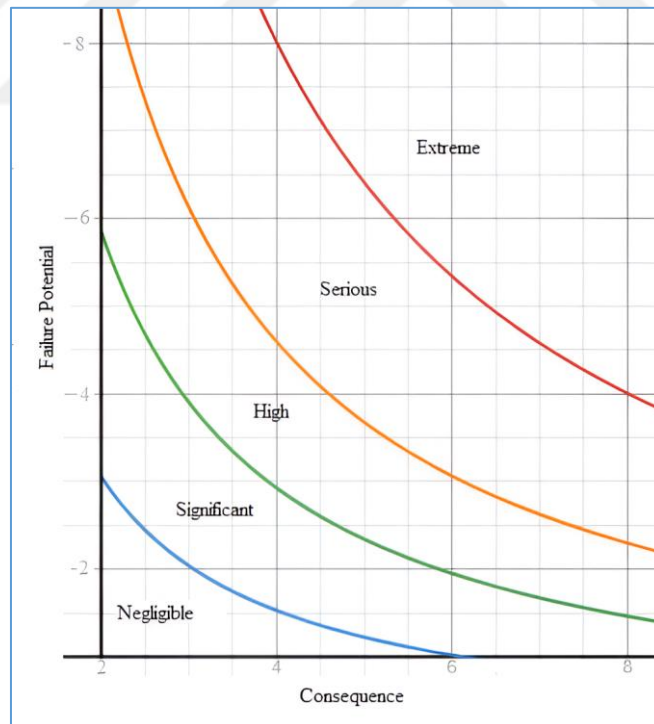


Figure 3.2: Representation of Risk Classes

3.8 Boundary and Limitations of the Model

Boundary selection is a fundamental step in constructing a dynamic system model. While increasing the level of detail in the model can enhance its resolution, it may also reduce the model's validity, particularly when working with index-based values and qualitative variables. Consequently, it is essential to select variables based on their relevance to the objectives and scope of the study (Erbayat, 2024). In this study, the variables used in the model are classified into three categories: endogenous, exogenous, and excluded. The variables selected for the consequence and failure analyses are presented in Table 3.45 and Table 3.46, respectively.

The most important limitation of the model is that it only includes the impacts within the selected risk body, which is a community or a settlement downstream of a tailings dam. In most cases, collapse of a tailings dam impacts more than one community through the course of a river or stream. Studied model excludes the impacts outside the boundary of determined risk body. Although the model is capable of the assessment of risk within whole course of a stream containing several communities, the need for several site studies and huge data requirement makes the model more impracticable. Moreover, outside economic losses and environmental impacts are also excluded in the model because of boundary limitation. The model concentrates on the water and soil pollution that are the most profound impacts in tailings dam failures. Air pollution is excluded in consequence assessment because of limited and very short-lasting impact during failure events. Another limitation of the model is that it does not take account the temporary residents in consequence assessment. The model only focuses on life and health losses, and social and economic impacts on the selected community. In other words, the model estimates the changes in community due to tailings dam collapse. Impacts on temporary residents like visitors, outside labors coming to work, and tourists are not included in the consequence assessment. This may lead the underestimation of absolute risk in region or nation-wise.

Although some scores given to some parameters changes over time, failure analysis of the model is static in general sense. In other words, the model presumes that variables do not change in time. Therefore, impacts of possible climate change over the modelled period is excluded. Another excluded factor is the human induced course of actions like sabotages or attacks, although they can cause the failure of a tailings dam.

Table 3.45 The Boundaries Chart for Consequence Analysis

Endogenous	Exogeneous	Excluded
Life loss	Economic Support	Impacts Outside of Risk Body
Loss of health		Outside Economic Loss
Displacement		Indirect (Outside) Environmental Impacts
Poverty		Air Pollution
Unrest		Temporary residents or visitors
Vulnerability		
Impact on Water		
Impact on Soil		

Table 3.46 The Boundaries Chart for Failure Analysis

Endogenous	Exogeneous	Excluded
Failure Modes	External management factors	Climate change
Dam Type	Extreme hydraulic events	Sabotages and attacks
Design and construction factors	Natural hazards	
Flood control measures	Seismicity	
Seepage and drainage facilities	Groundwater condition	
Construction material	Subsidence	
Dam characteristics		
Erosion measures		
Foundation properties		
Internal management factors		
Safety management factors		

CHAPTER 4

DEVELOPMENT OF THE SYSTEM DYNAMICS MODEL FOR THE COMBINED RISK ASSESSMENT OF MULTIPLE TAILINGS DAMS

4.1 Introduction

The developed combined risk assessment model concentrates on a potentially affected community living downstream of the multiple tailings dams. The community is denoted as a risk body and treated as a system with certain borders. Key features of the failure and consequence assessment methodologies are outlined. It is emphasized that the applied methodologies must address the complex, dynamic, and nonlinear characteristics of the risks involved. This necessitates the application of systems thinking, which involves analysing and understanding phenomena by considering interconnected wholes rather than separate components.

Gary and Shahidi (2011) stated that system dynamics, as a particular application of systems thinking, has developed from the original works of Forrester (Forrester, 1961) and the subsequent developmental work by Coyle (Coyle, 1977) and Richardson (Richardson and Pugh, 1981). System dynamics provides a framework for addressing dynamic complexity, where the relationship between cause and effect may not be clear. It is based on nonlinear dynamics and feedback control theory, and it establishes formal mathematical models, tests them, and provides a simulation to describe complex systems with nonlinear and dynamic features.

Development of a system dynamics (SD) model for combined risk assessment involves five main stages shown in Figure 4.1. The first stage includes initial development based on literature review and peer to peer meetings with experts. Subsystems, factors or parameters of the model are determined in this stage.

Extended surveys are conducted with two different expert panels, one for failure potential assessment and another for consequence assessment. Survey results are evaluated based on fuzzy logic analysis in the third stage. Details of the expert surveys and evaluation of survey results are given in Section 3.4. In the fourth stage weights, constants and related equations describing interdependencies between factors are inserted in the model, hence a fuzzy SD model are generated. The fifth and the last stage involves the insertion of the values determined for failure potential and consequences into the SD model and validation of SD model with case studies. If the final version of the model does not give adequate results and not simulate the cases properly, then the SD model is revised and subsequent stages are repeated.

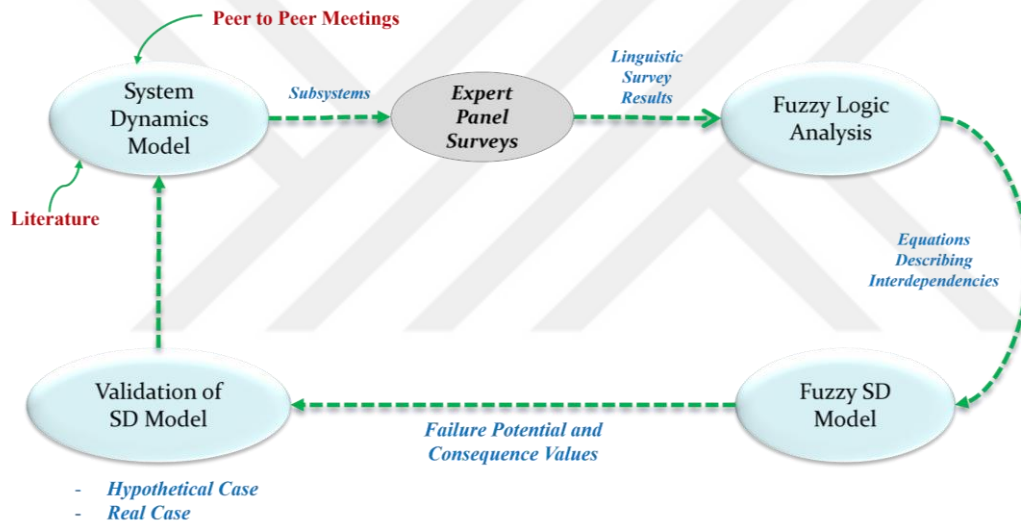


Figure 4.1 Flowchart of Development Stages of System Dynamics Model

4.2 Subsystems of the Stock and Flow Diagram Model

A system dynamics model utilizing a stock-and-flow diagram was developed to simulate the system, as it facilitates the representation of quantitative relationships between various factors. Stella is a popular software tool specifically designed for building and simulating system dynamics models.

Stella uses a drag-and-drop interface with four fundamental building blocks (see Table 4.1):

- Stocks (Rectangles): These represent accumulations or reservoirs within the system.
- Flows (Pipes with Arrows): These represent the rates at which stocks change. They are the activities that add to or subtract from a stock
- Converters (Circles): These are used for constants, auxiliary variables, or mathematical expressions that influence flows or other converters. They can convert inputs into outputs, hold parameters, or represent intermediate calculations.
- Connectors (Curved Lines with Arrows): These show the causal relationships and information flows between elements.

The simulation proceeds in discrete time steps. These times steps can vary from minutes to years depending on the purpose of the user. At each step, Stella calculates:

- The values of all converters.
- The rates of all flows based on their influencing converters and stocks.
- The new values of all stocks by adding or subtracting the calculated flows over the defined time step.

The time step chosen in proposed model is the year, which means that annual changes are calculated over the simulation period. Daily and monthly variations or seasonal changes are not simulated.

The constructed model consists of parameters organized into two primary subsystems: consequence and failure potential. The consequence subsystem is further divided into three subcomponents: human health, social and economic life, and the environment.

The model structure and factors were defined from feedbacks of experts in related fields and guidance documents. The dependencies between the factors were quantified by defining equations in the model. The stock-and-flow diagram was

constructed using Stella Architect software, with the diagram's components derived from the building blocks presented in Table 4.1.

Table 4.1 The Building Blocks of a Stock-and-Flow Model

Building Block	Name	Explanation
	Reservoir	The type of stock that passively accumulates its inflows minus any outflows.
	Module	Subsystems that are connectible to other subsystems.
	Converter	The main building blocks that convert inputs into outputs. It can hold constant value, define external inputs, and calculate equations or graphical functions.
	Flow	Flows fill and drain stocks. The flows can be in one direction or bi-directional.
	Connector	The element that connects variables to each other. Connectors indicate an immediate effect.

4.3 Consequence Subsystems

Magnitude of the consequence is ultimately dependent on the affected area due to amount of outflow volume from a tailings dam in case of a collapse or a failure. Therefore, closed dams and abandoned dams, since their deposition was ceased, are modeled as a static model. In other words, since affected area does not change the consequence remains the same assuming that variables of the risk body will be unchanged. On the other hand, in case of active dams, deposition continues and amount of affected area changes with time. This necessitates a dynamic model in which the consequence varies with time.

4.3.1 Human Health Subsystem

The consequence factor Human Health is calculated by a function of sum of the number of fatalities and the number of people lost their health, where its details are given in Chapter 3.5.1.

The overall view of the stock-and-flow diagram of the Human Health subsystem for inactive dams is shown in Figure 4.2. As shown in following figure, the model is constructed using the converters which include three types: Converters providing inputs only, converters taking inputs and providing outputs, and converters providing output only.

For inactive dams (static case), main output of the subsystem is calculated by the converter namely *Human Health* which takes inputs from the converter *HH*. The converter *HH* takes inputs from the converter *PLL* and the converter *PLH* which takes inputs from the converter *APLH* and the converter *VPLH*. The same procedure is valid for the other converters. Since the system is modeled as a static model, the converters take constant values.

Converters providing only inputs to the model shown in Figure 4.2, e.g., *Toxicity*, *Quickness of Rescue Services*, take user defined values or values from associated parameters in tables given in Chapter 3.5.1.

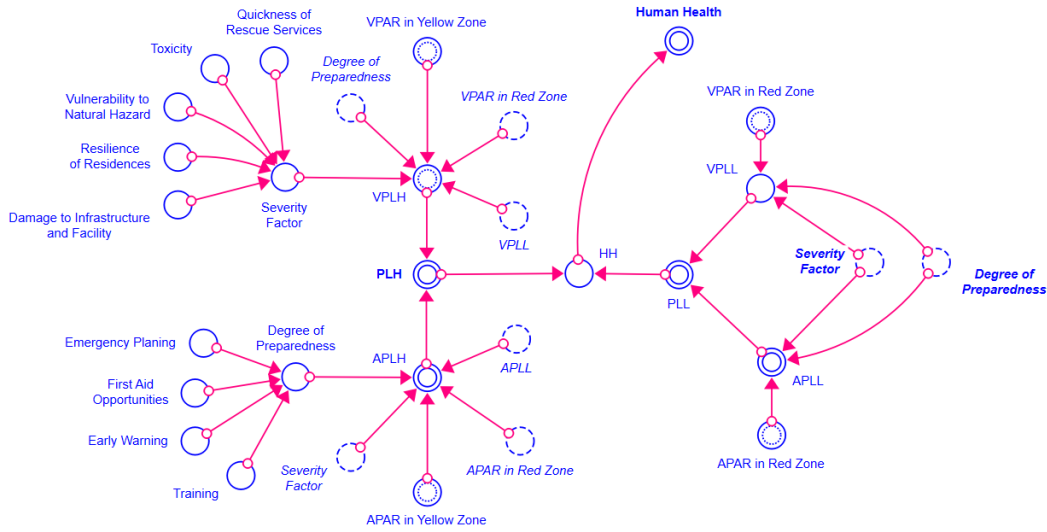


Figure 4.2: Stock-and-Flow Diagram of the Human Health Subsystem (Inactive Dam, Static Case)

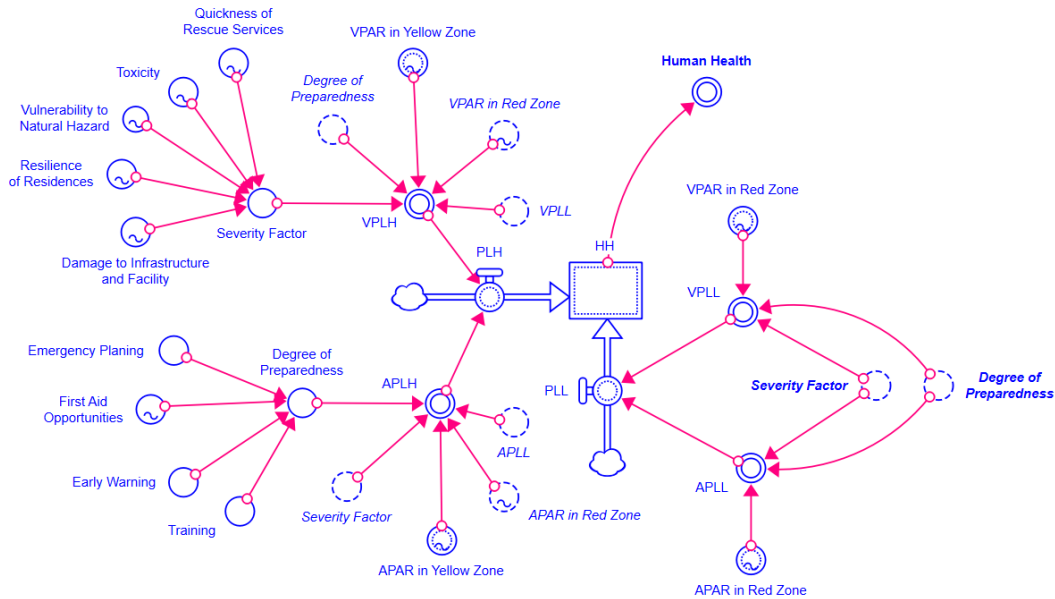


Figure 4.3: Stock-and-Flow Diagram of the Human Health Subsystem (Active Dam, Dynamic Case)

For active dams (dynamic case), main output of the subsystem is calculated by the converter namely *Human Health*. Different from the inactive dam case it takes inputs from the stock *HH*. Initial value of this stock is 0 and takes inputs from the flow

regulator *PLH* and the flow regulator *PLL* which takes inputs from the converter *APLL* and the converter *VPLL* (see Figure 4.3). When the system is modeled as a dynamic model, converters take functions defining associated changes in converters with time when appropriate.

The expressions of the diagram parameters are shown Table 4.2.

Table 4.2 Diagram Parameters and Variables of the Human Health Subsystem

Name	Type	Variable explanation	Equation/Value	Input Source
Human Health	Converter	Human Health factor for inactive dam	If (HH) > 0 then Human Health= log (HH), else 0	Connected Converter
Human Health (t)	Converter	Human Health factor for active dam	If (HH) > 0 then Human Health= log (HH) else 0	Connected Stock
HH (t)	Stock	Human Health factor for active dam	Initial value = 0	Connected Flow Regulators
HH	Converter	Human Health factor for inactive dam	PLL+ PLH	Connected Converters
PLL (t)	Flow Regulator	Additional number of loss of lives or fatalities	APLL + VPLL	Connected Converters
PLL	Converter	Number of loss of lives or fatalities	APLL + VPLL	Connected Converters
PLH (t)	Flow Regulator	Additional Loss of Health factor for active dam	APLH+ VPLH	Connected Converters
PLH	Converter	Loss of Health factor for inactive dam	APLH+ VPLH	Connected Converters
APAR in Red Zone	Converter	Number active people at risk in Red Zone	Number	User defined
VPAR in Red Zone	Converter	Number vulnerable people at risk in Red Zone	Number	User defined
APAR in Yellow Zone	Converter	Number active people at risk in Yellow Zone	Number	User defined
VPAR in Yellow Zone	Converter	Number vulnerable people at risk in Yellow Zone	Number	User defined
APLL	Converter	Loss of economically active people	APAR in Red Zone *[(1-(Degree of Preparedness - Severity Factor))/2]	Connected Converters
VPLL	Converter	Loss of vulnerable people	VPAR in Red Zone *[(1-(Degree of Preparedness - Severity Factor))/2]	User defined

Table 4.2 Diagram Parameters and Variables of the Human Health Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
APLH	Converter	Number of active people lost their health due to event	(APAR in Yellow Zone) *[(1- (Degree of Preparedness - Severity Factor))/2] + (APAR in Red Zone - APLL)	Connected Converters
VPLH	Converter	Number of vulnerable people lost their health due to event	(VPAR in Yellow Zone) *[(1- (Degree of Preparedness - Severity Factor))/2] + (VPAR in Red Zone - VPLL)	Connected Converters
Severity Factor	Converter	Factor for severity of the event	[0.23(Toxicity) +0.21(Damage to Infrastructure and Facilities) +0.21(Quickness of rescue services) +0.17(Resilience of residences) +0.18(Vulnerability to Natural Hazards)]/2	Connected Converters
Degree of Preparedness	Converter	Degree of Preparedness	[0.27(Emergency Planning) + 0.24(First Aid Opportunities) + 0.26(Early Warning System) +0.23(Training)]/2	Connected Converters
Toxicity	Converter	Toxicity index for human health	User defined score value	Table 3.14
Damage to Infrastructure and Facilities	Converter	Damage to infrastructure and facilities index	User defined score value	Table 3.14
Quickness of rescue services	Converter	Index for quickness of outside rescue services in reaching the risk body	User defined score value	Table 3.14
Resilience of residences	Converter	Index for structural strength of residences	User defined score value	Table 3.14
Vulnerability to Natural Hazards	Converter	Vulnerability of the area to natural hazards	User defined score value	Table 3.14
Emergency Planning	Converter	Index for Emergency planning	User defined score value	Table 3.15
First Aid Opportunities	Converter	Index for First aid opportunities	User defined score value	Table 3.15
Early Warning	Converter	Index for Early warning opportunities	User defined score value	Table 3.15
Training	Converter	Training condition of the community	User defined score value	Table 3.15

4.3.2 Social and Economic Life Subsystem

The same procedure is valid for Social and Economic Life subsystem as in case of Human Health. The overall view of the stock-and-flow diagram of the Social and Economic Life subsystem for inactive dams and active dam and expressions of the diagram parameters are shown in Figure 4.4, Figure 4.5 and Table 4.3, respectively.

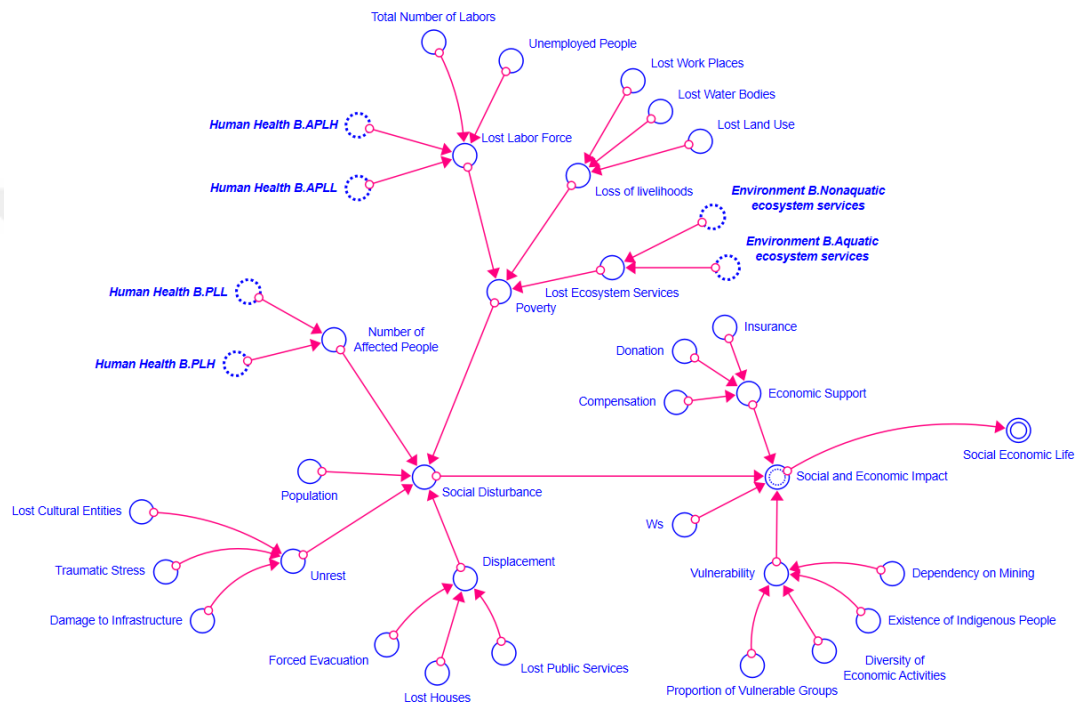


Figure 4.4: Stock-and-Flow Diagram of the Social and Economic Life Subsystem (Inactive Dam, Static Case)

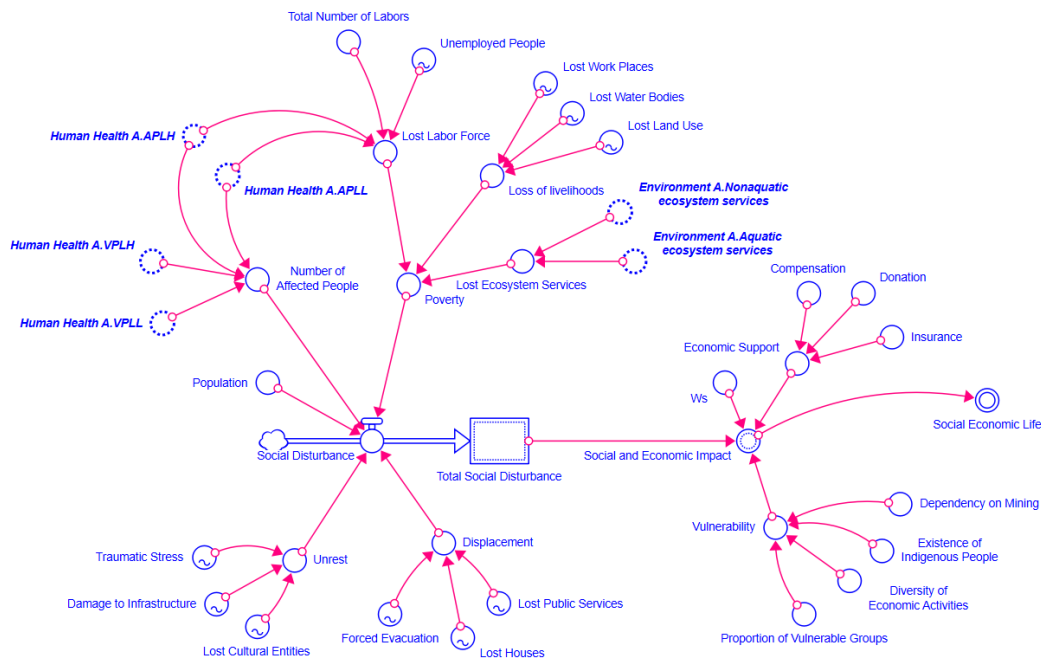


Figure 4.5: Stock-and-Flow Diagram of the Social and Economic Life Subsystem (Active Dam, Dynamic Case)

Table 4.3 Diagram Parameters and Variables of the Social and Economic Life Subsystem

Name	Type	Variable explanation	Equation/Value	Input Source
Social Economic Life	Converter	Social and Economic Life index for consequence assessment for active dam	$e(\text{Social and Economic Impact})$	Connected Converter
Social and Economic Impact	Converter	Social and Economic Life index for consequence assessment for inactive dams	$V + \text{SoD} - W_s * ES$	Connected Converters
Social and Economic Impact (t)	Converter	Social and Economic Life index for consequence assessment for active dams	$V + \text{TSD} - W_s * ES$	Connected Converters and Stock
Total Social Disturbance (TSD)	Stock	Cumulative sum of Social Disturbance	Initial value = 0	Connected Flow Regulator
Social Disturbance (SoD)	Flow Regulator	Social Disturbance factor for active dam	$0.24(\text{Unrest}) + 0.27(\text{Displacement}) + 0.23(\text{Poverty}) + 0.26[\log(\text{Number of Affected People}) / \log(\text{Population})]$	Connected Converters

Table 4.3 Diagram Parameters and Variables of the Social and Economic Life Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Social Disturbance (SoD)	Converter	Social Disturbance factor for inactive dam	$0.24(\text{Unrest}) + 0.27(\text{Displacement}) + 0.23(\text{Poverty}) + 0.26 [\log(\text{Number of Affected People}) / \log(\text{Population})]$	Connected Converters
Number of Affected People	Converter	Total number of potential fatalities and people lost their health	$\text{PLL} + \text{PLH}$	
Unrest	Converter	Unrest index for Social Disturbance	$[W_1(\text{Traumatic Stress}) + W_2(\text{Loss of Cultural Entities}) + W_3(\text{Damage to Facilities})]/6$	Connected Converters and user defined constants
Traumatic Stress	Converter	Index for traumatic stress	User defined score value	Table 3.16
Damage to Infrastructure	Converter	Damage to social infrastructure and facilities	User defined score value	Table 3.16
Loss of Cultural Entities	Converter	Loss of cultural entities	User defined score value	Table 3.16
Population	Converter	Number of people living within Risk Body	Number	User defined
Displacement	Converter	Index for Displacement	$[W_1(\text{Forced Evacuation}) + W_2(\text{Loss of Houses}) + W_3(\text{Loss of Public Services})]/6$	Connected Converters and user defined constants
Forced Evacuation	Converter	Forced evacuation of the area due to potential failure	User defined score value	Table 3.17
Loss of Houses	Converter	Loss of houses	User defined score value	Table 3.17
Loss of Public Services	Converter	Loss of public services	User defined score value	Table 3.17
Poverty	Converter	Index for Poverty	$W_1(\text{Loss of Livelihoods}) + W_2(\text{Loss of Labor force}) + W_3(\text{Loss of Ecosystem Services})$	Connected Converters and user defined constant
Loss of Livelihoods	Converter	Index for Poverty	$W_1(\text{Loss of Land Use}) + W_2(\text{Loss of Water Bodies}) + W_3(\text{Loss of Workplaces})$	Connected Converters and user defined constants
Loss of Land Use	Converter	Ratio of land use lost due to event	Number	User defined Eq. (3.15)
Loss of Water Bodies	Converter	Ratio of water bodies lost due to event	Number	User defined Eq. (3.16)
Loss of Workplaces	Converter	Ratio of workplaces lost due to event	Number	User defined Eq.(3.17)
Loss of Ecosystem Services	Converter	Index for total ecosystem services lost	$W_1(\text{Aquatic Ecosystem Services}) + W_2(\text{Nonaquatic Ecosystem Services})$	Connected Converters and user defined constants

Table 4.3 Diagram Parameters and Variables of the Social and Economic Life Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Lost Labor Force	Converter	Loss of labor force	$(APLL + APLH + \text{Unemployed People}) / \text{Total number of Labors}$	Connected Converters and user defined values
Total Number of Labors	Converter	Total labor force within risk body	Number	User defined
Unemployed People	Converter	Unemployment ratio due loss of working opportunities	Number	User defined
Vulnerability (V)	Converter	Vulnerability of community to the event	$0.24(\text{Dependency on Mining}) + 0.24(\text{Diversity of Economic Activities}) + 0.26(\text{Proportion of Vulnerable Groups}) + 0.26(\text{Existence of Indigenous People})$	Connected Converters
Dependency on Mining	Converter	Number of employees working in the mine/Total number of employed people	Number	User defined
Diversity of Economic Activities	Converter	$1 / \text{Number of main economic activities}$	Number	User defined
Proportion of Vulnerable Groups	Converter	$\text{Population of vulnerable groups} / \text{Population of community}$	Number	User defined
Existence of Indigenous People	Converter	If (Indigenous people exist) Then (1) Else (0)	Number	User defined
Economic Support (ES)	Converter	Economic support	$[0.39(\text{Donations}) + 0.38(\text{Compensations}) + 0.23(\text{Insurance})] / 2$	Connected Converters
Donations	Converter	Potential donations in case of the event	User defined score value	Table 3.18
Compensation	Converter	Potential compensations provided in case of the event	User defined score value	Table 3.18
Insurance	Converter	Insurance opportunities	User defined score value	Table 3.18
Ws	Converter	Weighting factor for Economic Support	0.55 (Determined through expert evaluation)	User defined constant

4.3.3 Environment Subsystem

The overall view of the stock-and-flow diagram of the Environment subsystem for inactive dams and active dam and expressions of the diagram parameters are shown in Figure 4.6, Figure 4.7 and Table 4.4, respectively.

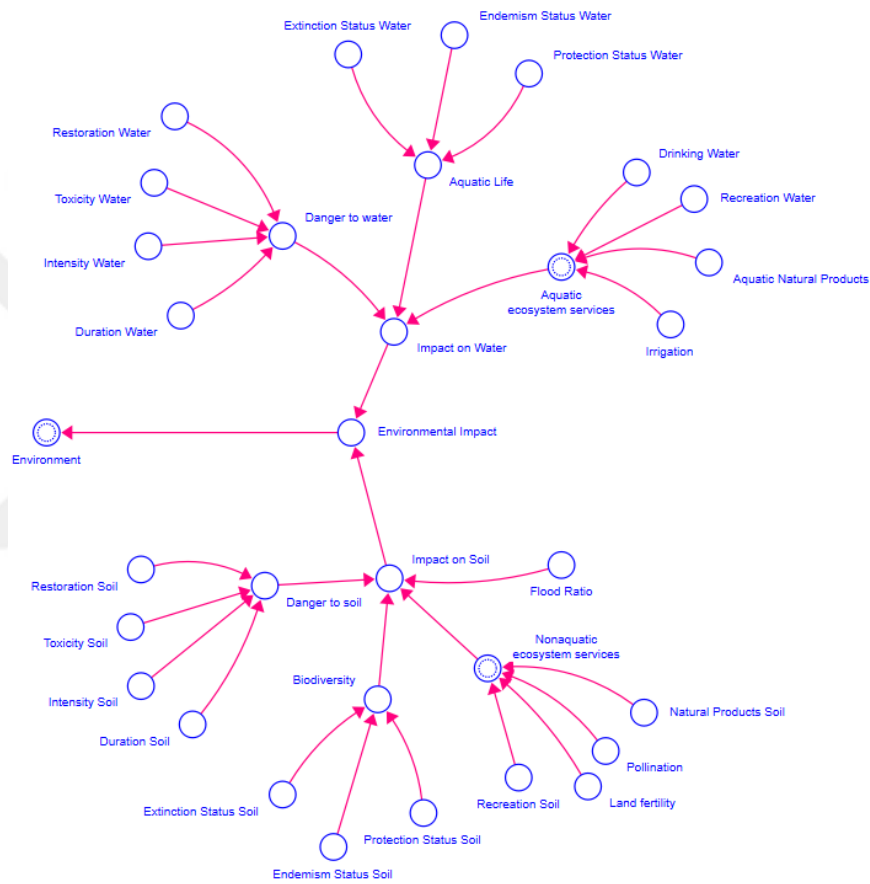


Figure 4.6: Stock-and-Flow Diagram of the Environment (Inactive Dam)

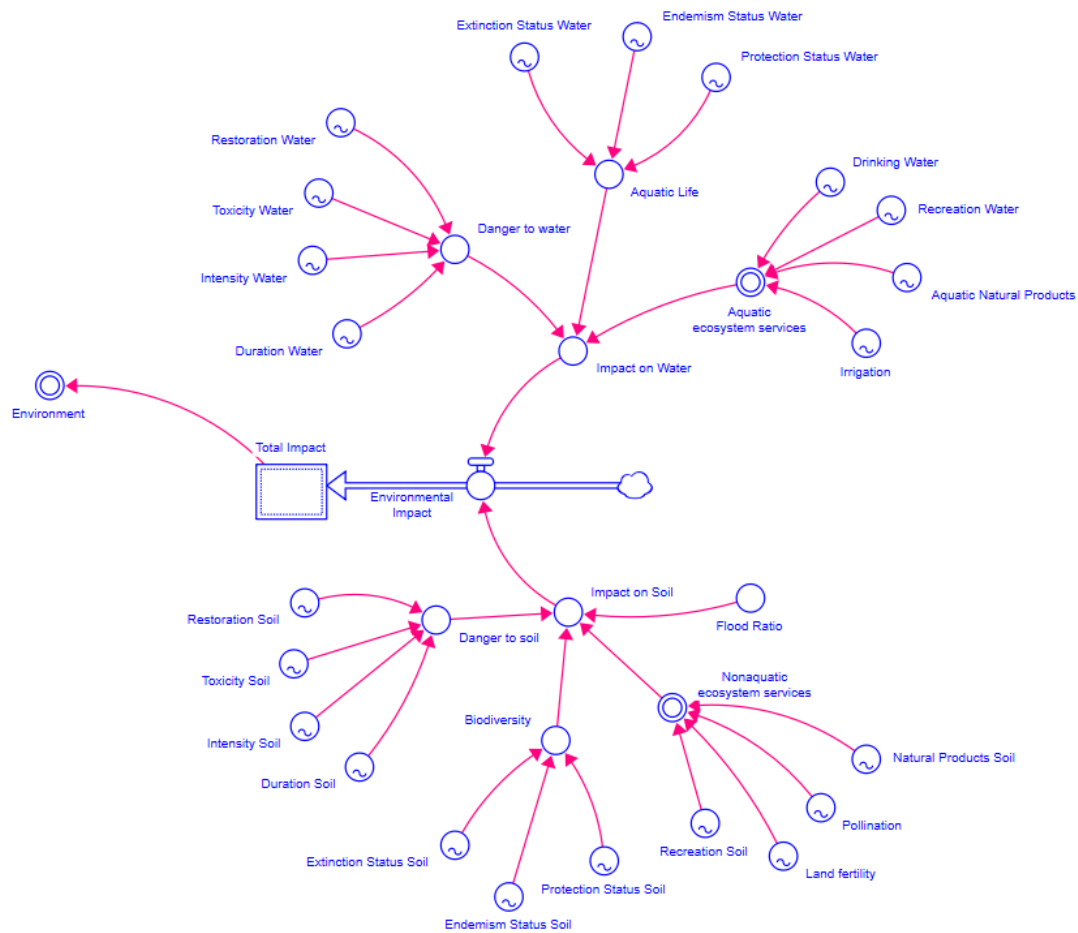


Figure 4.7: Stock-and-Flow Diagram of the Environment (Active Dam)

Table 4.4 Diagram Parameters and Variables of the Environment Subsystem

Name	Type	Variable explanation	Equation/Value	Input Source
Environment	Converter	Environment factor for active dam	$e^{(Total\ Impact)}$	Connected Converter
Total Impact (t)	Stock	Cumulative sum of Environmental Impact	Initial value =0	Connected Flow Regulator
Environmental Impact	Converter	Environmental Impact	$W_1(Impact\ on\ Soil) + W_2(Impact\ on\ Water\ Body)$	Connected Converters and user defined constants
Environmental Impact (t)	Flow Regulator	Environmental Impact	$W_1(Impact\ on\ Soil) + W_2(Impact\ on\ Water\ Body)$	Connected Converters and user defined constants
Impact on Soil	Converter	Impact on soil environment	$(Danger\ to\ Soil * Flood\ Ratio) * (Biodiversity + Nonaquatic\ Ecosystem\ Services)/2$	Connected Converters

Table 4.4 Diagram Parameters and Variables of the Environment Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Flood Ratio	Converter	Weighting factor for areal extent of impact (Flooded Area/Total Area)	Number	User defined value
Danger to Soil	Converter	Index for pollution characteristics of tailings on soil environment	$(\text{Toxicity Soil} + \text{Intensity Soil} + \text{Duration Soil} + \text{Restoration Soil})/8$	Connected Converters
Biodiversity	Converter	Index for characteristics of nonaquatic bio-environment	$(\text{Extinction Status Soil} + \text{Endemism Status Soil} + \text{Protection Status Soil})/6$	Connected Converters
Nonaquatic Ecosystem Services	Converter	Index for ecosystem services provided by soil environment	$(W_1 \text{Land Fertility} + W_2 \text{Pollination} + W_3 \text{Natural Products Soil} + W_4 \text{Recreation Soil})/2$	Connected Converters
Impact on Water Body	Converter	Impact on water body	$\text{Danger to Water} * (\text{Aquatic Life} + \text{Aquatic Ecosystem Services})/2$	Connected Converters
Danger to Water	Converter	Index for pollution characteristics of tailings on water environment	$(\text{Toxicity Water} + \text{Intensity Water} + \text{Duration Water} + \text{Restoration Water})/8$	Connected Converters
Aquatic Life	Converter	Index for characteristics of aquatic bio-environment	$(\text{Extinction Status Water} + \text{Endemism Status Water} + \text{Protection Status Water})/6$	Connected Converters
Aquatic Ecosystem Services	Converter	Index for aquatic ecosystem services	$(W_1 \text{Drinking Water} + W_2 \text{Irrigation} + W_3 \text{Aquatic Natural Products} + W_4 \text{Recreation Water})/2$	Connected Converters
Toxicity Soil	Converter	Toxicity index for soil	User Defined Score Value	Table 3.19
Intensity Soil	Converter	Intensity index for soil	User Defined Score Value	Table 3.19
Duration Soil	Converter	Duration index for soil	User Defined Score Value	Table 3.19
Restoration Soil	Converter	Restoration index for soil	User Defined Score Value	Table 3.19
Extinction Status Soil	Converter	Extinction status index for soil	User Defined Score Value	Table 3.20
Endemism Status Soil	Converter	Endemism status index for soil	User Defined Score Value	Table 3.20
Protection Status Soil	Converter	Protection status index for soil	User Defined Score Value	Table 3.20
Land Fertility	Converter	Land fertility	User Defined Score Value	Table 3.21
Pollination	Converter	Pollination index for soil	User Defined Score Value	Table 3.21
Natural Products Soil	Converter	Natural products index for soil	User Defined Score Value	Table 3.21
Recreation Soil	Converter	Recreation index for soil	User Defined Score Value	Table 3.21
Extinction Status Water	Converter	Extinction status index for water	User Defined Score Value	Table 3.23
Endemism Status Water	Converter	Endemism status index for water	User Defined Score Value	Table 3.23
Protection Status Water	Converter	Protection status index for water	User Defined Score Value	Table 3.23
Toxicity Water	Converter	Toxicity index for water	User Defined Score Value	Table 3.22

Table 4.4 Diagram Parameters and Variables of the Environment Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Intensity Water	Converter	Intensity index for water	User Defined Score Value	Table 3.22
Duration Water	Converter	Duration index for water	User Defined Score Value	Table 3.22
Restoration Water	Converter	Restoration index for water	User Defined Score Value	Table 3.22
Drinking Water	Converter	Drinking water	User Defined Score Value	Table 3.24
Irrigation	Converter	Irrigation	User Defined Score Value	Table 3.24
Aquatic Natural Products	Converter	Natural products index for aquatic resources	User Defined Score Value	Table 3.24
Recreation Water	Converter	Recreation index for water	User Defined Score Value	Table 3.24

4.4 Failure Potential Subsystems

The approach applied to consequences is assumed to be applicable to the failure potential of a tailings dam, depending on the dam's status. In this model, the failure potential variables are assumed to remain constant in the event of collapses or failures of inactive dams. In contrast, certain failure potential variables of active dams change over time, thus necessitating a dynamic model. As a result, the failure potential subsystem is further subdivided into two distinct subsystems: the active life failure potential subsystem and the inactive life failure potential subsystem.

4.4.1 Active Life Failure Potential Subsystem

The overall view of the stock-and-flow diagram of the Active Life Failure Potential subsystem for active dam and expressions of the diagram parameters are shown in Figure 4.8 and Table 4.5, respectively.

It should be paid attention that in Figure 4.8 some of the converters such as seismicity, construction material, seepage and drainage facilities are connected to more than one flow regulators providing overriding effects in determination of failure mode.

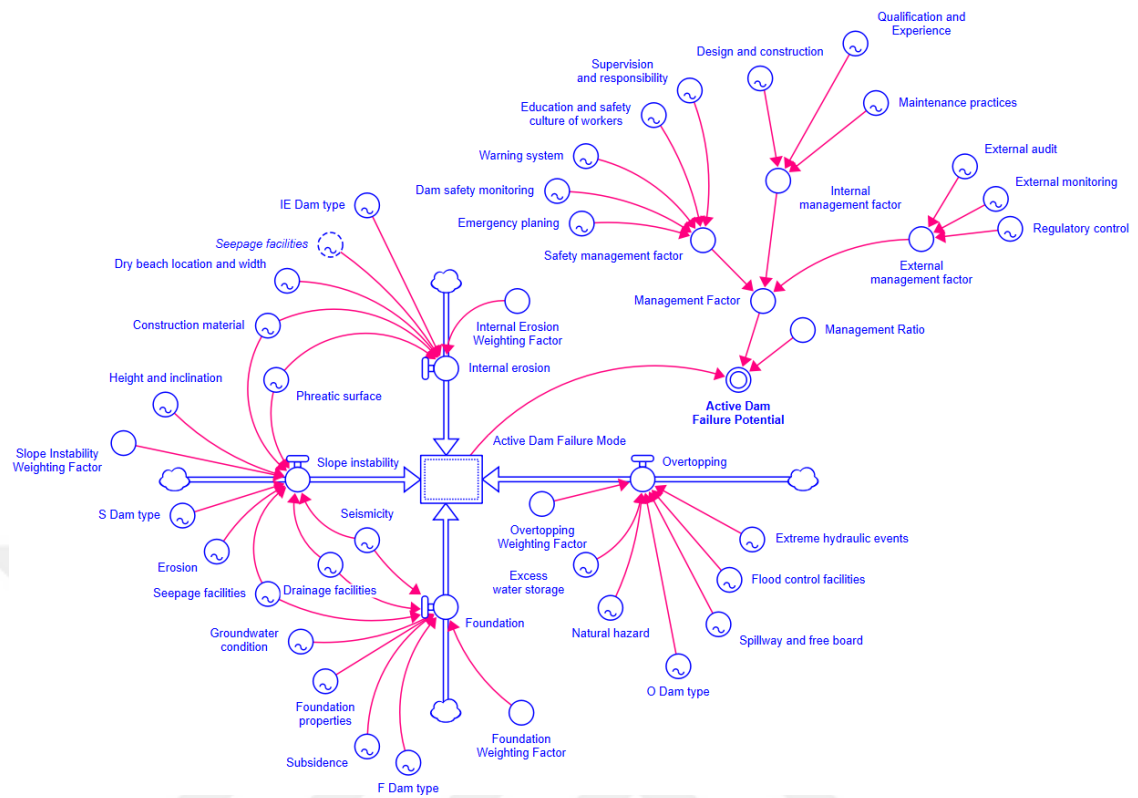


Figure 4.8: Stock-and-Flow Diagram of the Active Life Failure Potential Subsystem

Table 4.5 Diagram Parameters and Variables of the Active Life Failure Potential Subsystem

Name	Type	Variable explanation	Equation/Value	Input Source
Active Dam Failure Potential	Converter	Index value for failure potential of an active dam.	$EXP (1 + \text{Active Dam Failure Mode} - \text{Management Ratio} \times \text{Management Factor})$	Connected Converters
Management Factor	Converter	Index value for management factor	$0.36(\text{Dam Safety Management Factor}) + 0.34(\text{Internal Management Factor}) + 0.30(\text{External Management Factor})$	Connected Converters
Management Ratio	Converter	Weighting factor for Management Factor	0.77 (Determined through expert evaluation)	User defined constant
Active Dam Failure Mode	Stock	Active Dam Failure Mode	Initial value = 0	Dimensionless
Overtopping	Flow Regulator	Index value for overtopping failure mode	$(\text{Overtopping Weighting Factor}) * [0.18(\text{Extreme hydraulic events}) + 0.21(\text{Natural hazards}) + 0.20(\text{Excess Water Storage}) + 0.21(\text{Flood control facilities or spillway and freeboard}) + 0.20(\text{Dam type})]/6$	Connected Converters

Table 4.5 Diagram Parameters and Variables of the Active Life Failure Potential Subsystem
(cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Overtopping Weighting Factor	Converter	Weighting factor of overtopping mode for Active Dam Failure Mode	0.21 (Determined through expert evaluation)	User defined constant
Extreme Hydraulic Events	Converter	Extreme hydraulic events	User Defined Score Value	Table 3.26
Natural Hazards	Converter	Natural hazards	User Defined Score Value	Table 3.26
Excess Water Storage	Converter	Excess water storage	User Defined Score Value	Table 3.26
Flood Control Facilities	Converter	Flood control facilities	User Defined Score Value	Table 3.26
Spillway and Free Board	Converter	Spillway and free board	User Defined Score Value	Table 3.26
O Dam type	Converter	Index value of dam type for overtopping mode	User Defined Score Value	Table 3.26
Slope Instability	Flow Regulator	Index value for slope instability failure mode	(Slope Instability Weighting Factor) * [0.13(Seismicity)+ 0.14(Construction material) +0.12(Seepage facilities) + 0.11(Drainage facilities) + 0.10(Phreatic surface) +0.14(Height and inclination) + 0.13(Erosion)+ 0.13(Dam type)]/6	Connected Converters
Slope Instability Weighting Factor	Converter	Weighting factor of Slope Instability mode for Active Dam Failure Mode	0.31 (Determined through expert evaluation)	User defined constant
Seismicity	Converter	Index value of seismicity of dam site	User Defined Score Value	Table 3.27
Construction material	Converter	Material used for construction of dam	User Defined Score Value	Table 3.27
Seepage Facilities	Converter	Seepage facilities	User Defined Score Value	Table 3.27
Drainage Facilities	Converter	Drainage facilities	User Defined Score Value	Table 3.27
Phreatic Surface	Converter	Water level in deposited tailings and dam structure	User Defined Score Value	Table 3.27
Height and inclination	Converter	Height and inclination of slope of dam	User Defined Score Value	Table 3.27
Erosion	Converter	Index value of erosion characteristics of dam wall	User Defined Score Value	Table 3.27
S Dam type	Converter	Dam type for slope instability mode	User Defined Score Value	Table 3.27

Table 4.5 Diagram Parameters and Variables of the Active Life Failure Potential Subsystem (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Internal Erosion	Flow Regulator	Internal erosion failure mode	$(\text{Internal Erosion Weighting Factor}) * [0.20(\text{Seepage facilities}) + 0.20(\text{Construction material}) + 0.20(\text{Phreatic surface}) + 0.17(\text{Dry beach width}) + 0.23(\text{Dam type})] / 6$	Connected Converters
Internal Erosion Weighting Factor	Converter	Weighting factor of Internal Erosion mode for Active Dam Failure Mode	0.20 (Determined through expert evaluation)	User defined constant
Dry beach location and width	Converter	Dry beach location and width	User Defined Score Value	Table 3.28
IE Dam type	Converter	Dam type for internal erosion mode	User Defined Score Value	Table 3.28
Foundation	Flow Regulator	Foundation failure mode	$(\text{Foundation Weighting Factor}) * [0.13(\text{Drainage facilities}) + 0.12(\text{Seepage facilities}) + 0.16(\text{Foundation properties}) + 0.15(\text{Groundwater condition}) + 0.15(\text{Seismicity}) + 0.15(\text{Subsidence}) + 0.14(\text{Dam type})] / 6$	Connected Converters
Foundation Weighting Factor	Converter	Weighting factor of Foundation mode for Active Dam Failure Mode	0.28 (Determined through expert evaluation)	
Foundation properties	Converter	Index for Foundation properties	User Defined Score Value	Table 3.29
Groundwater condition	Converter	Index for Groundwater condition	User Defined Score Value	Table 3.29
Subsidence	Converter	Index for Subsidence	User Defined Score Value	Table 3.29
F Dam type	Converter	Index for Dam type for foundation failure mode	User Defined Score Value	Table 3.29
External Management Factor	Converter	External Management Factor	$[0.34(\text{External Audit}) + 0.33(\text{External monitoring}) + 0.33(\text{Regulatory control})] / 6$	Connected Converters
External Audit	Converter	External Audit	User Defined Score Value	Table 3.32
External monitoring	Converter	External monitoring	User Defined Score Value	Table 3.32
Regulatory control	Converter	Regulatory control	User Defined Score Value	Table 3.32
Internal Management Factor	Converter	Internal Management Factor	$[0.34(\text{Design and construction}) + 0.35(\text{Qualification and Experience}) + 0.31(\text{Maintenance practices})] / 6$	Connected Converters
Design and construction	Converter	Design and construction	User Defined Score Value	Table 3.31
Qualification and experience	Converter	Qualification and experience	User Defined Score Value	Table 3.31

Table 4.5 Diagram Parameters and Variables of the Active Life Failure Potential Subsystem
(cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Maintenance practices	Converter	Maintenance practices	User Defined Score Value	Table 3.31
Safety Management Factor	Converter	Safety Management Factor	$[0.22(\text{Dam safety monitoring}) + 0.21(\text{Warning system}) + 0.18(\text{Emergency planning}) + 0.19(\text{Training and safety culture of workers}) + 0.20(\text{Supervision and responsibility})]/6$	Connected Converters
Dam safety monitoring	Converter	Dam safety monitoring	User Defined Score Value	Table 3.30
Warning system	Converter	Warning system	User Defined Score Value	Table 3.30
Emergency planning	Converter	Emergency planning	User Defined Score Value	Table 3.30
Education and safety culture of workers	Converter	Education and safety culture of workers	User Defined Score Value	Table 3.30
Supervision and responsibility	Converter	Supervision and responsibility	User Defined Score Value	Table 3.30

4.4.2 Inactive Life Failure Potential Subsystem

The overall view of the stock-and-flow diagram of the Inactive Life Failure Potential subsystem for closed dam and abandoned dam and expressions of the diagram parameters are shown in Figures 4.9 and 4.10, and Tables 4.6 and 4.7 respectively.

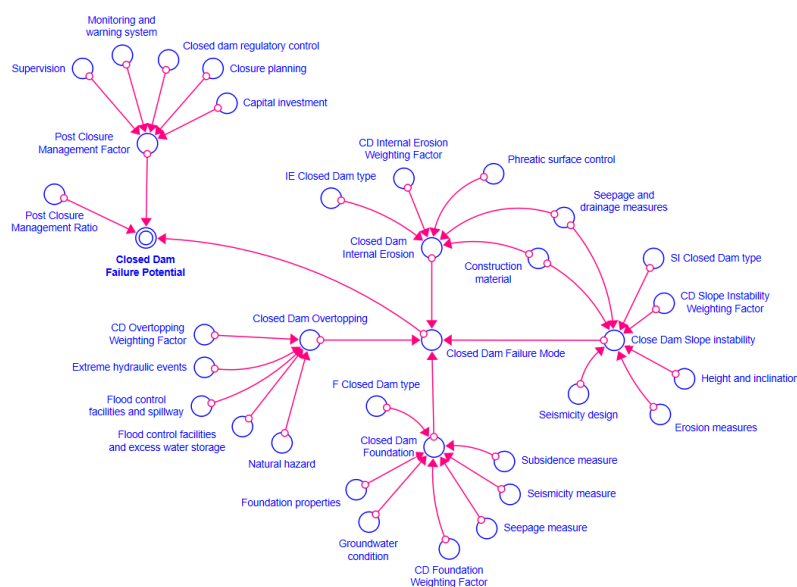


Figure 4.9: Stock-and-Flow Diagram of the Inactive Life Failure Potential Subsystem (Closed Dam)

Table 4.6 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Closed Dams

Name	Type	Variable explanation	Equation/Value	Input Source
Closed Dam Failure Potential	Converter	Closed Dam Failure Potential	EXP (1+ Closed Dam Failure Mode-Post Closure Management Ratio* Post Closure Management Factor)	Connected Converters
Closed Dam Failure Mode	Converter	Sum of failure modes for closed dam	Closed Dam Overtopping+ Closed Dam Slope Instability + Closed Dam Internal Erosion + Closed Dam Foundation	Connected Converters
CD Overtopping Weighting Factor	Converter	Weight of Closed Dam Overtopping Mode	0.20 (Determined through expert evaluation)	User defined constant
Closed Dam Overtopping	Converter	Closed dam overtopping failure mode	$[0.31(\text{Extreme hydraulic events}) + 0.34(\text{Natural hazards}) + 0.35(\text{Flood control facilities})]/6$	Dimensionless
Extreme Hydraulic Events	Converter	Index for Extreme Hydraulic Events	User Defined Score Value	Table 3.33
Natural hazards	Converter	Index for Natural hazards	User Defined Score Value	Table 3.33
Flood control facilities and excess water storage	Converter	Index for Flood control facilities and excess water storage	User Defined Score Value	Table 3.33
Flood control facilities and spillway	Converter	Index for Flood control facilities and spillway	User Defined Score Value	Table 3.33
CD Slope Instability Weighting Factor	Converter	Weight of Closed Dam Slope Instability Mode	0.32 (Determined through expert evaluation)	User defined constant
Closed Dam Slope Instability	Converter	Index for Closed dam slope instability mode	$[0.17(\text{Seismicity}) + 0.19(\text{Construction material}) + 0.15(\text{Seepage and drainage measures}) + 0.16(\text{Height and inclination}) + 0.16(\text{Erosion measures}) + 0.17(\text{SI Closed Dam type})]/6$	Connected Converters
Seismicity design	Converter	Seismicity design for slope instability	User Defined Score Value	Table 3.34
Construction material	Converter	Index for Construction material for slope instability	User Defined Score Value	Table 3.34
Seepage and drainage measures	Converter	Seepage and drainage measures for slope instability	User Defined Score Value	Table 3.34
Height and inclination	Converter	Index for Height and inclination	User Defined Score Value	Table 3.34
Erosion measures	Converter	Erosion measures for slope instability	User Defined Score Value	Table 3.34

Table 4.6 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Closed Dams (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
SI Closed Dam type	Converter	Index for dam type for slope instability	User Defined Score Value	Table 3.34
CD Internal Erosion Weighting Factor	Converter	Weight of Closed Dam Internal Erosion Mode	0.31 (Determined through expert evaluation)	User defined constant
Closed Dam Internal Erosion	Converter	Closed dam internal erosion failure mode	$[0.24(\text{Seepage and drainage facilities}) + 0.27(\text{Construction material}) + 0.24(\text{Phreatic surface control}) + 0.25(\text{IE Closed Dam type})]/6$	Connected Converters
Phreatic surface control	Converter	Phreatic surface control for Internal Erosion	User Defined Score Value	Table 3.35
IE Closed Dam type	Converter	Index for Closed Dam type for Internal Erosion mode	User Defined Score Value	Table 3.35
CD Foundation Weighting Factor	Converter	Weight of Closed Dam Foundation Mode	0.27 (Determined through expert evaluation)	User defined constant
Closed Dam Foundation	Converter	Closed dam foundation failure mode	$[0.16(\text{Seepage measures}) + 0.20(\text{Foundation properties}) + 0.16(\text{Groundwater condition}) + 0.17(\text{Seismicity measure}) + 0.16(\text{Subsidence measure}) + 0.15(\text{F Closed Dam type})]/6$	Connected Converters
Foundation properties	Converter	Index for Foundation properties	User Defined Score Value	Table 3.36
Groundwater condition	Converter	Groundwater condition	User Defined Score Value	Table 3.36
Subsidence measure	Converter	Subsidence measure	User Defined Score Value	Table 3.36
Seismicity measure	Converter	Seismicity measure	User Defined Score Value	Table 3.36
Seepage measure	Converter	Seepage measure	User Defined Score Value	Table 3.36
F Closed Dam type	Converter	Index for Closed Dam type for Foundation failure mode	User Defined Score Value	Table 3.36
Post Closure Management Ratio	Converter	Weighting factor for Post Closure Management Factor	0.70 (Determined through expert evaluation)	User defined constant
Post Closure Management Factor	Converter	Post Closure Management Factor	$[0.19(\text{Supervision}) + 0.20(\text{Monitoring and warning system}) + 0.19(\text{Regulatory control}) + 0.22(\text{Closure planning}) + 0.20(\text{Capital investment})]/6$	Connected Converters
Monitoring and warning system	Converter	Index for Monitoring and warning system	User Defined Score Value	Table 3.37

Table 4.6 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Closed Dams (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Closed dam regulatory control	Converter	Index for Closed dam regulatory control	User Defined Score Value	Table 3.37
Closure Planning	Converter	Index for Closure Planning	User Defined Score Value	Table 3.37
Capital investment	Converter	Index for Capital investment	User Defined Score Value	Table 3.37
Supervision	Converter	Index for Supervision	User Defined Score Value	Table 3.37

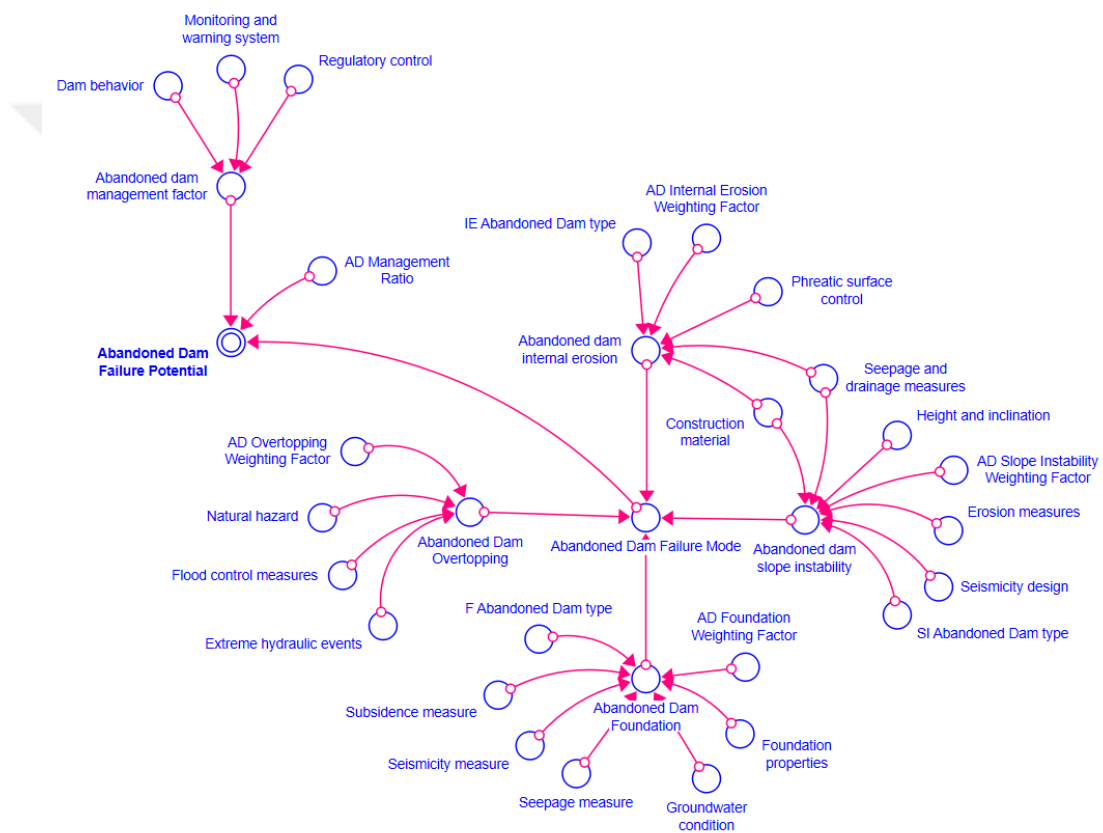


Figure 4.10: Stock-and-Flow Diagram of the Inactive Life Failure Potential Subsystem (Abandoned Dam)

Table 4.7 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Abandoned Dams

Name	Type	Variable explanation	Equation/Value	Input Source
Abandoned Dam Failure Potential	Converter	Abandoned Dam Failure Potential	EXP (1 + Abandoned Dam Failure Mode – (AD Management Ratio * Abandoned Dam Management Factor)	Connected Converters
Abandoned Dam Failure Mode	Converter	Index for Abandoned Dam Failure Mode	Overtopping + Slope Instability + Internal Erosion + Foundation	Connected Converters
AD Overtopping Weighting Factor	Converter	Weight of Abandoned Dam Overtopping Mode	0.19 (Determined through expert evaluation)	User defined constant
Abandoned Dam Overtopping	Converter	Abandoned dam overtopping failure mode	[0.33(Extreme hydraulic events) +0.35(Natural hazards) +0.32(Flood control measures)]/6	Connected Converters and user defined constant
Extreme hydraulic events	Converter	Extreme hydraulic events	User Defined Score Value	Table 3.38
Natural hazard	Converter	Natural hazard	User Defined Index Value	Table 3.38
Flood control measures	Converter	Flood control measures	User Defined Index Value	Table 3.38
AD Slope Instability Weighting Factor	Converter	Weight of Abandoned Dam Slope Instability Mode	0.33 (Determined through expert evaluation)	User defined constant
Abandoned Dam Slope Instability	Converter	Abandoned dam slope instability	[0.17(Seismicity)+0.19(Construction material) +0.14(Seepage and drainage measures) +0.17(Height and inclination) +0.16(Erosion measures) +0.17(SI Abandoned Dam type)]/6	Connected Converters and user defined constant
Seismicity design	Converter	Seismicity design	User Defined Score Value	Table 3.39
Construction material	Converter	Construction material	User Defined Score Value	Table 3.39
Seepage and drainage measures	Converter	Seepage and drainage measures	User Defined Score Value	Table 3.39
Height and inclination	Converter	Height and inclination	User Defined Score Value	Table 3.39
Erosion measures	Converter	Erosion measures	User Defined Score Value	Table 3.39
SI Abandoned Dam type	Converter	Index for Abandoned Dam type for Slope Instability mode	User Defined Score Value	Table 3.39
AD Internal Erosion Weighting Factor	Converter	Weight of Abandoned Dam Internal Erosion Mode	0.21 (Determined through expert evaluation)	User defined constant

Table 4.7 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Abandoned Dams (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Abandoned Dam Internal Erosion	Converter	Abandoned dam internal erosion failure mode	$[0.24(\text{Seepage and drainage measures}) + 0.26(\text{Construction material}) + 0.25(\text{Phreatic surface control}) + 0.25(\text{IE Abandoned Dam type})]/6$	Connected Converters and user defined constant
Phreatic surface control	Converter	Phreatic surface control for Internal Erosion	User Defined Score Value	Table 3.40
IE Abandoned Dam type	Converter	Index for Abandoned Dam type for Internal Erosion	User Defined Score Value	Table 3.40
AD Foundation Weighting Factor	Converter	Weight of Abandoned Dam Foundation Mode	0.27 (Determined through expert evaluation)	User defined constant
Abandoned Dam Foundation	Converter	Abandoned dam foundation failure mode	$[0.15(\text{Seepage measures}) + 0.19(\text{Foundation properties}) + 0.16(\text{Groundwater condition}) + 0.18(\text{Seismicity measure}) + 0.16(\text{Subsidence measure}) + 0.16(\text{F Abandoned Dam type})]/6$	Connected Converters and user defined constant
Foundation properties	Converter	Index for Foundation properties	User Defined Score Value	Table 3.41
Groundwater condition	Converter	Groundwater condition for Foundation failure mode	User Defined Score Value	Table 3.41
Subsidence measure	Converter	Subsidence measure for Foundation failure mode	User Defined Score Value	Table 3.41
Seismicity measure	Converter	Seismicity measure for Foundation failure mode	User Defined Score Value	Table 3.41
Seepage measure	Converter	Seepage measure for Foundation failure mode	User Defined Score Value	Table 3.41
F Abandoned Dam type	Converter	Index for Abandoned Dam type for Foundation failure mode	User Defined Score Value	Table 3.41
AD Management Ratio	Converter	Weighting factor for Abandoned Dam Management Factor	0.66 (Determined through expert evaluation)	User defined constant
Abandoned Dam Management Factor	Converter	Abandoned Dam Management Factor	$[0.34(\text{Monitoring and warning system}) + 0.32(\text{Regulatory control}) + 0.34(\text{Dam behavior})]/6$	Connected Converters and user defined constant

Table 4.7 Diagram Parameters and Variables of the Inactive Life Failure Potential Subsystem for Abandoned Dams (cont'd)

Name	Type	Variable explanation	Equation/Value	Input Source
Monitoring and warning system	Converter	Index for Monitoring and warning system for	User Defined Score Value	Table 3.42
Regulatory control	Converter	Index for Regulatory control	User Defined Score Value	Table 3.42
Dam behavior	Converter	Index for Dam behavior	User Defined Score Value	Table 3.42

4.5 Individual Risk Subsystem

Individual risks induced by single tailings dam are estimated by the product of potential of a tailings dam to fail and resulted consequences of its failure (Table 4.8). Therefore, Individual Risk Subsystem contains two modules. One of them is the consequence module having three sub-modules for Human Health, Social and Economic Life, Environment subsystems (Figure 4.11). Other module is Failure Potential containing associated failure potential subsystem.

In order to construct a risk model, status of the dam should be determined and associated failure potential subsystem should be selected accordingly. If the dam is an active dam, in other words if tailings deposition continues, Active Life Failure Potential Subsystem is selected for the risk assessment (Figure 4.12). If the dam is closed or abandoned, then one of the appropriate failure potentials is selected under Inactive Life Failure Potential Subsystem is selected.

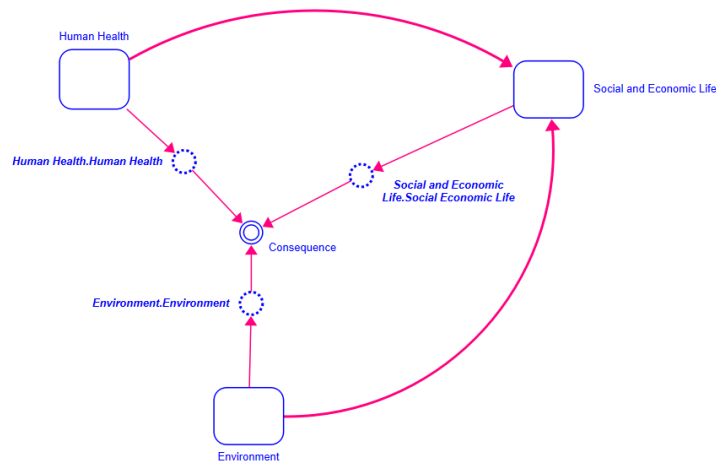


Figure 4.11: Representation of Consequence Module and Its Submodules

Table 4.8 Individual Risk Model Variables

Name	Type	Variable explanation	Equation	Units
Risk	Converter	Risk value induced by failure a tailings dam	$\text{Consequence} \times \text{Failure Potential}$	Dimensionless
Consequence	Converter	Consequence index value for risk assessment	$\text{Human Health} + \text{Social and Economic Life} + \text{Environment}$	Dimensionless
Failure Potential	Converter	Failure potential index value for risk assessment	Failure Potential	Dimensionless

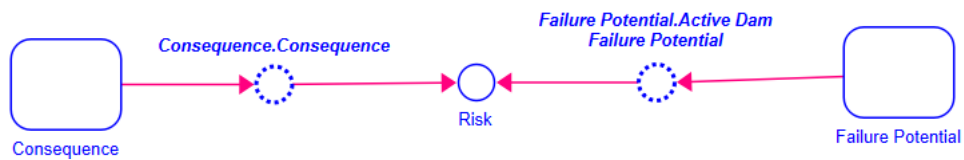


Figure 4.12: Representation of Individual Risk Subsystem of An Active Dam

4.6 Combined Risk Assessment

A risk body may be threatened by not only a single tailings dam but also multiple tailings dams located upstream, especially near or on the streams. Such scenarios necessitate a combined risk assessment of the multiple tailings dams. The concept of combined risk can be represented as a chain of events. This chain includes the

identified potential sources (tailings dams), the receptor (community), and the pathways of tailings flow between them. The combined risk encompasses the collapses or failures of the tailings dams, which together contribute to the total risk of a given event.

4.6.1 Identification of Risk Sources and Dam Status

The first step in conducting a combined risk assessment is to identify upstream tailings dams that may cause a threat to a designated community (risk body). One initial approach to identifying risk sources involves running a flow model for the upstream sources to determine whether they affect the risk body. However, this approach may require intensive work, especially when there are a large number of risk sources.

One approach to reducing the workload is to employ the method proposed by Rico et al. (2008). They compiled the information on historic tailings dam failures with the purpose to establish simple correlations between tailings ponds geometric parameters and the hydraulic characteristics of floods resulting from released tailing. In their study, researchers plotted “tailings dam” factor ($H \times V_F$) versus the outflow run-out distance ($D_{\max}$) and created a regression line (Figure 4.13) and the empirical Equation 4.1.

$$D_{\max} = 1.61 (H \times V_F)^{0.66}, r^2 = 0.57 \quad (4.1)$$

where H is dam height in meters and V_F is released outflow volume in 10^6 m^3 . They pointed out that a major limitation to the application of Equation 4.2 consists of the uncertainty of potential tailings outflow volume (V_F) in the case of failure. Additionally, they stated that in average one-third of the tailings and water at the decant pond is released during dam failures.

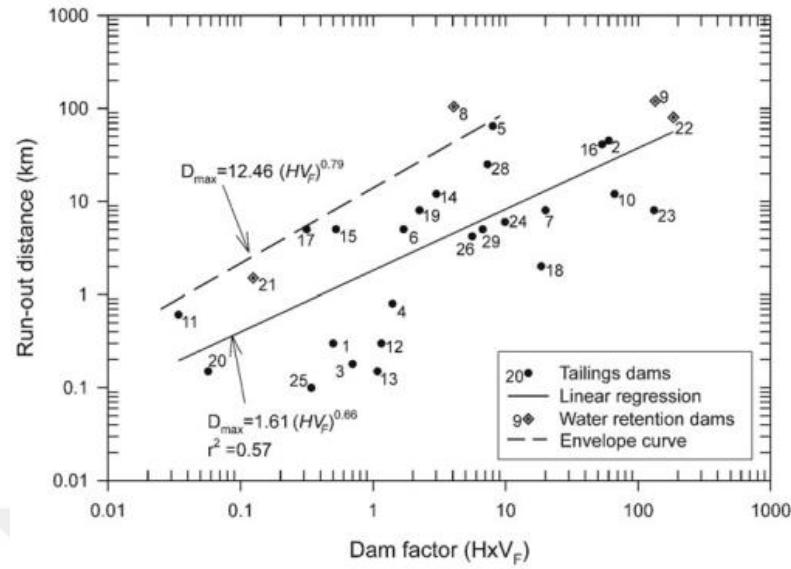


Figure 4.13: Dam Factor Vs. Run-Out Distance of Tailings (Rico et. al. 2008)

The envelope curve is described by Equation 4.2. It represents the maximum volume of tailings that could be released in the most extreme scenario, where the pond volume is completely emptied following the dam failure.

$$D_{\max} = 12.46 (H \times V_F)^{0.79} \quad (4.2)$$

After identifying potential sources, the status of each tailings dam should be assessed to facilitate the integration of the relevant subsystems. Active dams can be assessed using a dynamic model since tailings deposition continues and downstream inundation area in case of a failure changes with time depending on amount of runout material. Inactive dams can be modelled as a static model because fixed amount of material contained in the dam reservoir, assuming the downstream conditions does not change with time.

4.6.2 Identification of Event and Risk Segments

In this study two types of failure event are identified and different approaches are applied to estimate the combined risk of each event.

- i. Independent Event: The failure event is designated as independent event when the upstream tailings dams are in separate catchments and failure of any tailings dam cannot affect the failure of another one.
- ii. Cascading Event: When the failure of any tailings dam affects the failure of other tailings dams, the failure event is called as cascading event. This type of events occurs if any tailings dam is located upstream of another one.

To conduct a combined risk assessment, each risk body should be divided into "risk segments" based on exposure conditions from individual tailings dams. The risks from these separate segments are then combined to calculate the overall risk to the risk body. The coverage (inundation) areas of tailings flows from distinct sources are determined within the body, and segments influenced by both single and multiple sources are identified.

4.6.3 Methodology for Risk Combination

Since the risk is the product of consequence and failure potential, combined risk is defined as the product of combined consequence and combined failure potential in this study, as given in Equation (4.3).

$$\text{Combined Risk} = \text{Combined Consequence} \times \text{Combined Failure Potential} \quad (4.3)$$

Combined consequence is the aggregation of consequences induced by individual tailings dams.

In case of an independent event the combined consequence from Tailings Dam A and Tailings Dam B is estimated using Equation (4.4) assuming that the consequence factor value within a segment is uniformly distributed (see Figure 4.14).

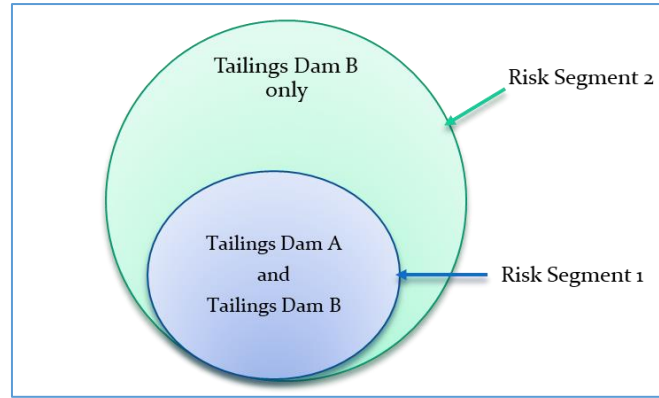


Figure 4.14 Risk Segments of an Independent Event

$$\text{Combined Consequence} = \text{MAX}\left(\frac{\text{Area A}}{\text{Area B}} \times C_B, C_A\right) + \left(\frac{\text{Area B} - \text{Area A}}{\text{Area B}}\right) \times C_B \quad (4.4)$$

where *Area A* is the coverage area of the segment which is exposed to failure of both Tailings Dam A and Tailings Dam B (Risk Segment 1), *Area B - Area A* is the coverage area of the segment which is exposed to failure of Tailings Dam B only (Risk Segment 2), and *Area B* > *Area A*. C_A and C_B denote the consequences of the Tailings Dam A failure and Tailings Dam B failure, respectively.

Presence of additional tailings dams emerges extra failure potentials upstream of risk body. Therefore, the combined failure potential of the associated risk body should be higher than individual failure potential of tailings dams and it is estimated using failure potential of Tailings Dam A (FP_A) and Tailings Dam B (FP_B) (see Equation (4.5)).

$$\begin{aligned} \text{Combined Failure Potential} \\ = \text{MAX}(FP_A, FP_B) + \left(\frac{\text{MAX}(FP_A, FP_B)}{FP_A + FP_B}\right) \times \text{MIN}(FP_A, FP_B) \end{aligned} \quad (4.5)$$

In case of a cascading event, failure of upstream tailings dam (Tailings Dam B) can result in the failure of downstream tailings dam (Tailings Dam A). Therefore, the amount of runout material is higher than separate runouts hence the extent of

coverage area ($AreaAB$). In this case, the combined risk is estimated using Equation (4.6).

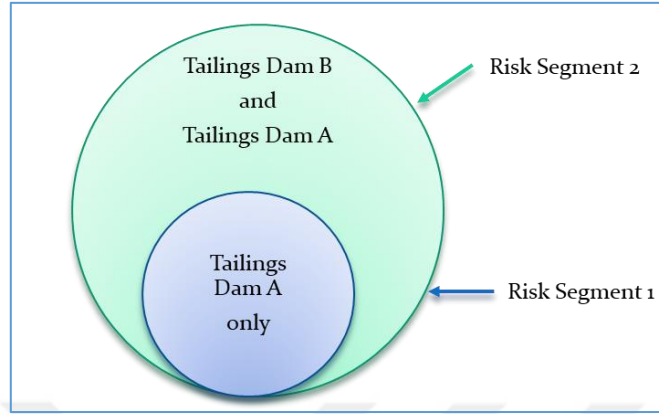


Figure 4.15 Risk Segments of a Cascading Event

$$\text{Combined Risk} = FP_B \times C_{AreaAB} + \frac{FP_B}{FP_B + FP_A} FP_A \times C_{AreaA} \quad (4.6)$$

Where FP_B and FP_A are the failure potential of Tailings Dam B and Tailings Dam A, C_{AreaAB} and C_{AreaA} are the consequence within $AreaAB$ and $AreaA$, respectively.

4.6.4 Combined Risk Subsystem

Combined Risk Subsystem contains two modules. One of them is the Dam A module having two sub-modules for Consequence A and Failure Potential A subsystems. Other module is Dam B containing associated consequence and failure potential subsystems. Combined risk subsystem of an independent event and a cascading event are seen in Figure 4.16 and Figure 4.17, respectively. Combined risk is calculated using connected converters in the subsystem and converters from contained modules.

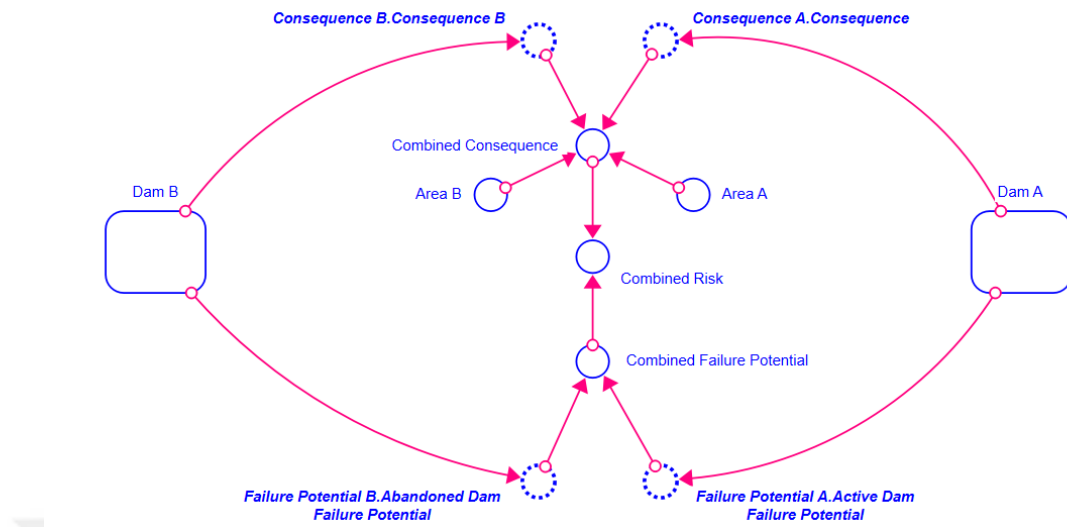


Figure 4.16: Representation of Combined Risk Subsystem of an independent event and its submodules

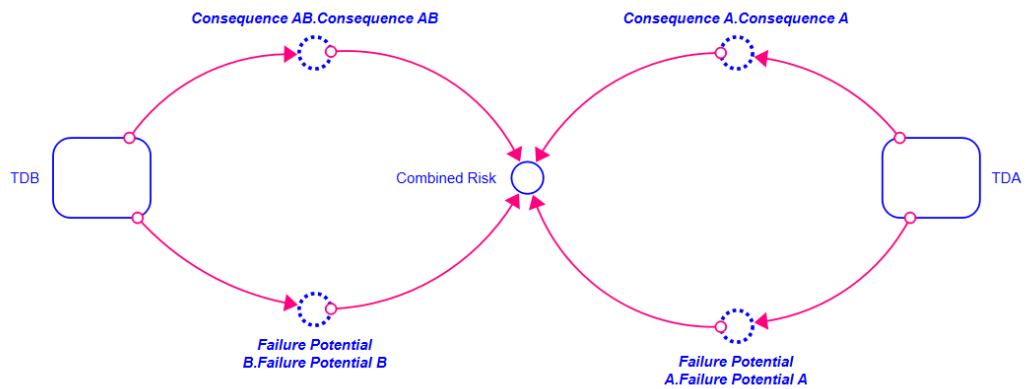


Figure 4.17: Representation of Combined Risk Subsystem of a cascading event and its submodules

CHAPTER 5

VERIFICATION AND VALIDATION OF THE DEVELOPED MODEL

5.1 Verification of the Developed Model by a Hypothetical Case

This section applies the developed system dynamics model to a hypothetical input dataset, which is intended to simulate the failure conditions of two tailings dams located upstream of a community and consequences of the event. It is important to note that the outcomes of the model are highly sensitive to the values of the parameters and the initial values of the variables. Consequently, varying scenarios may produce different results.

5.1.1 Risk Body and Event

In a hypothetical case, targeted community is a village located downstream of a two tailings dams. Tailings Dam A (TDA) is an active dam with 10 years of operational life, and Tailings Dam B (TDB) is an abandoned dam. Tailings stored in TDA is known to be hazardous to humans, whereas tailings in TDB is inert.

Following information is assumed to be gained during the site study. Targeted village has a population of 200 people. The number of people in vulnerable groups is 80, which is 40% of population. No indigenous people live in the study area. Main economic activities of the community are fishery, agriculture, beekeeping, and mining. Total number of people employed in those economic sectors is 120 of which 30 people are miners. There are 20 fishermen working in 3 fishing ponds located near the stream and its tributary. 60 farmers are using agricultural areas of 50

hectares. 10 people are beekeepers in the community. There are a medical unit and a school as public buildings, and a mosque as a cultural entity in the village.

5.1.2 Model Input

After execution of an appropriate flow model in annual basis, potentially flooded (affected) areas, slurry levels and slurry velocities are assumed to be determined. Analysis of the flooded area reveals the consequences of Tailings A failure and Tailing Dam given in Table 5.1 and Table 5.3, respectively. On the other hand, failure potential datasets are given in Table 5.2 and Table 5.4 for Tailings Dams A and B, respectively.

The model was run for a hypothetical failure of Tailings Dam A and Tailings Dam B using Stella Architect v.3.8.1. It is assumed that the affected areas were determined on an annual basis using a flow model, and corresponding changes in variables were incorporated into the risk model. The affected areas due to the failures of Tailings Dam A and Tailings Dam B are 10 hectares and 20 hectares, respectively. Figure 5.1 shows the input windows and respected values inserted to “*APAR in RED Zone*” and “*Damage to infrastructure and facilities*” parameters. As it seen from the following figure, tailings flow reaches the populated area when Tailings Dam A collapses after 7th year. Furter more, the value of 1 is inserted to the “*Damage to infrastructure and facilities*” parameter after 4th year because flow model reveals that the tailings flow damages the medical unit in the concerned settlement in the year 4. Table 5.1 presents the model inputs for this hypothetical case.

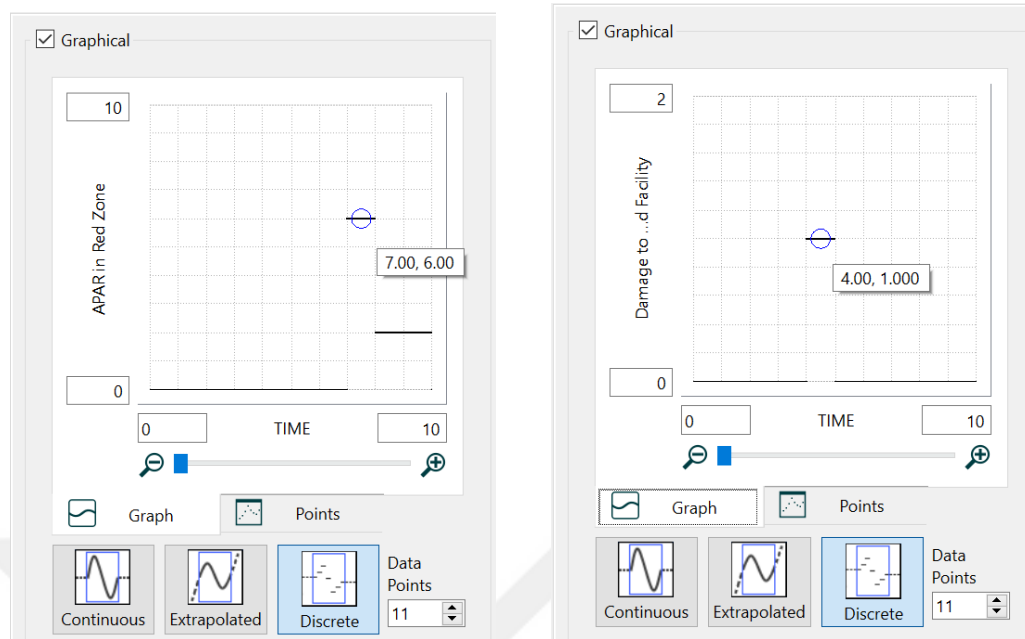


Figure 5.1: Screenshots of input windows for dynamic modelling

Table 5.1 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam A

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Human Health	APAR in RED Zone	APLL	10	Active people at risk in Red Zone	Eq. (3.1)
	VPAR in Red Zone	VPLL	6	Vulnerable people at risk in Red Zone	Eq. (3.1)
	APAR in Yellow Zone	APLH	8	Active people at risk in Yellow Zone	Eq. (3.1)
	VPAR in Yellow Zone	VPLH	4	Vulnerable people at risk in Yellow Zone	Eq. (3.1)
	Toxicity	Severity Factor	1	Hazardous tailings	Table 3.14
	Damage to Infrastructure and Facilities	Severity Factor	1	Medical unit is damaged	Table 3.14
	Quickness of rescue services	Severity Factor	1	Rescue services reach in 30 minutes.	Table 3.14
	Resilience of Residents	Severity Factor	2	Residences are mostly constructed with weak materials	Table 3.14
	Vulnerability to Natural Hazards	Severity Factor	1	Region is vulnerable to natural floods	Table 3.14

Table 5.1 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam A
(cont'd)

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Human Health	Emergency Planning	Degree of Preparedness	0	There is no emergency plan	Table 3.15
	First Aid Opportunities	Degree of Preparedness	2	Medical unit exists in affected area	Table 3.15
	Early Warning System	Degree of Preparedness	0	None	Table 3.15
	Training	Degree of Preparedness	0	None	Table 3.15
Social and Economic Life	Ws	Social and Economic Impact	0.55	Weight of Economic Support	Eq. (3.6)
	Traumatic Stress	Unrest	6	Loss of both active and vulnerable groups	Table 3.16
	Damage to Infrastructure	Unrest	4	Damage to drinking water sources and power lines	Table 3.16
	Loss of Cultural Entities	Unrest	2	Damage to mosque	Table 3.16
	Population	Vulnerability	200	Total number of people living in community	Eq. (3.7)
	Forced Evacuation	Displacement	2	Dam site is prone to extreme hydraulic events	Table 3.17
	Loss of Houses	Displacement	1	20 % of houses damaged (< 40 %)	Table 3.17
	Loss of Public Services	Displacement	3	Potential damage to medical service	Table 3.17
	Loss of Land Use	Poverty	0.3	Ratio (30 % of total land is affected)	Eq. (3.15)
	Loss of Water Bodies	Poverty	1	All the waterbodies are affected	Eq. (3.16)
	Loss of Workplaces	Poverty	0	Ratio (None of workplaces is affected)	Eq. (3.17)
	Total number of labors	Poverty	120	Number of active people	Eq. (3.18)
	Unemployed People	Poverty	20	Number of people lost their work opportunities	Eq. (3.18)
	Dependency on Mining	Vulnerability	0.25	Ratio (25 % of total labor force works in mining)	Eq. (3.9)
	Diversity of Economic Activities	Vulnerability	0.25	1/4 (4 main activities in community)	Eq. (3.9)
	Proportion of Vulnerable Groups	Vulnerability	0.4	Ratio (40 % of population)	Eq. (3.9)
	Existence of Indigenous People	Vulnerability	0	None	Eq. (3.9)

Table 5.1 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam A (cont'd)

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Social and Economic Life	Donations	Economic Support	1	Expected donation by public	Table 3.18
	Compensation	Economic Support	2	Compensation could be provided both mine owner and government	Table 3.18
	Insurance	Economic Support	0	None	Table 3.18
Environment	Flood Ratio	Impact on Soil	0.2	Ratio (20 % of total area is flooded)	(3.24)
	Toxicity Soil	Danger to Soil	2	Tailings contains toxic substances to soil	Table 3.19
	Intensity Soil	Danger to Soil	2	Contaminant source strength is expected to be decreasing within a prolonged time	Table 3.19
	Duration Soil	Danger to Soil	2	Pollution is expected to be permanent or long-lasting	Table 3.19
	Restoration Soil	Danger to Soil	2	Affected soil can be restored through major clean-up and restoration efforts	Table 3.19
	Extinction Status Soil	Index for Biodiversity	0	None	Table 3.20
	Endemism Status Soil	Index for Biodiversity	0	None	Table 3.20
	Protection Status Soil	Index for Biodiversity	0	None	Table 3.20
	Land Fertility	Non-aquatic Ecosystem Services	2	Loss of any income generating land	Table 3.21
	Pollination	Non-aquatic Ecosystem Services	2	Loss of lands covered by vegetation	Table 3.21
	Natural Products Soil	Non-aquatic Ecosystem Services	1	Loss of any natural products	Table 3.21
	Recreation Soil	Non-aquatic Ecosystem Services	1	Loss of lands having any recreational value	Table 3.21
	Extinction Status Water	Index for aquatic life	0	None	Table 3.23
	Endemism Status Water	Index for aquatic life	0	None	Table 3.23
	Protection Status Water	Index for aquatic life	0	None	Table 3.23
	Toxicity Water	Danger to Water	1	Tailings is non-toxic to water body	Table 3.22

Table 5.1 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam A (cont'd)

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Environment	Intensity Water	Danger to Water	1	Contaminant source strength is expected to be decreasing significantly within a short time	Table 3.22
	Duration Water	Danger to Water	1	Pollution is expected to be temporary or short-lasting	Table 3.22
	Restoration Water	Danger to Water	2	Affected water body can be restored through major clean-up and restoration efforts	Table 3.22
	Drinking Water	Aquatic Ecosystem Services	2	Water body provides drinking water	Table 3.24
	Irrigation	Aquatic Ecosystem Services	2	Lands are irrigated using the water body.	Table 3.24
	Aquatic Natural Products	Aquatic Ecosystem Services	2	Loss of any natural product with an economic importance	Table 3.24
	Recreation Water	Aquatic Ecosystem Services	1	Affected water body having any recreational value	Table 3.24

Table 5.2 Hypothetical Failure Potential Dataset for the Model Implementation for Tailings Dam A

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Active Life Failure Potential	Management Ratio	Active Dam Failure Potential	0.77	Weighting (77 %)	Eq. 3.23
	Extreme Hydraulic Events	Overtopping Mode	2	Site is prone to high snowmelt	Table 3.26
	Natural Hazards	Overtopping Mode	2	Site is prone to avalanche	Table 3.26
	Excess Water Storage	Overtopping Mode	4	Available volume < ½PMF	Table 3.26
	Flood Control Facilities	Overtopping Mode	0	Single-stage dam	Table 3.26
	Spillway and Free Board	Overtopping Mode	3	Spillway with less than 1 m free board	Table 3.26
	O Dam type	Overtopping Mode	2	Single-stage dam	Table 3.26
	Seismicity	Slope Instability Mode, Foundation Mode	4	PGA > 0.20g with proper design	Table 3.27
	Construction material	Slope Instability Mode, Internal Erosion	4	Earth fill	Table 3.27
	Seepage facilities	Slope Instability, Foundation, Internal Erosion modes	3	Active facilities (pumping)	Table 3.27
	Drainage facilities	Slope Instability, Foundation modes	3	Active facilities (decanting)	Table 3.27
	Phreatic Surface	Slope Instability, Internal Erosion modes	4	Passive control (internal zoning) without monitoring	Table 3.27

Table 5.2 Hypothetical Failure Potential Dataset for the Model Implementation for Tailings Dam A
(cont'd)

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Active Life Failure Potential	Height and inclination	Slope Instability	2	$\leq 27^\circ$	Table 3.27
	Erosion	Slope Instability Mode	2	Site is prone to extreme weather conditions	Table 3.27
	S Dam type	Slope Instability	1	Single-stage	Table 3.27
	Dry beach location and width	Internal Erosion Mode	2	Length of beach / Height of dam > 5	Table 3.28
	IE Dam type	Internal Erosion Mode	3	Single-stage	Table 3.28
	Foundation properties	Foundation Failure Mode	6	Weak and soft soils	Table 3.29
	Groundwater condition	Foundation Failure Mode	3	Sited on shallow unsaturated zone	Table 3.29
	Subsidence	Foundation Failure Mode	0	None	Table 3.29
	F Dam type	Foundation Failure Mode	3	Single-stage	Table 3.29
	External Audit	External Management	6	Systematic audit or technical review	Table 3.32
	External monitoring	External Management	6	Monitoring on request	Table 3.32
	Regulatory control	External Management	3	Irregular control	Table 3.32
	Design and construction	Internal Management	6	Construction with proper design	Table 3.31
	Qualification and experience	Internal Management	4	Qualified and experienced contractor and consultant	Table 3.31
	Maintenance practices	Internal Management	0	No incident during both construction and operation	Table 3.31
	Dam safety monitoring	Dam Safety Management	4	Monitoring of both dam movement and phreatic surface	Table 3.30
	Warning system	Dam Safety Management	3	Any means of warning system	Table 3.30
	Emergency planning	Dam Safety Management	6	Emergency planning in action	Table 3.30
	Training and safety culture of workers	Dam Safety Management	3	Only informative documents or guidelines	Table 3.30
	Supervision and responsibility	Dam Safety Management	4	Responsible site person and Engineer of record	Table 3.30
	Overtopping Weighting Factor	Failure Mode	0.21	Weighting (21 %)	Eq. (3.25)
	Slope Instability Weighting Factor	Failure Mode	0.31	Weighting (31 %)	Eq. (3.25)
	Internal Erosion Weighting Factor	Failure Mode	0.20	Weighting (20 %)	Eq. (3.25)
	Foundation Weighting Factor	Failure Mode	0.28	Weighting (28 %)	Eq. (3.25)

Table 5.3 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam B

Subsystem	Parameter	Factor	Value		Reference
Human Health	APAR in RED Zone	APLL	8	Active people at risk in Red Zone	Eq. (3.1)
	VPAR in Red Zone	VPLL	5	Vulnerable people at risk in Red Zone	Eq. (3.1)
	APAR in Yellow Zone	APLH	4	Active people at risk in Yellow Zone	Eq. (3.1)
	VPAR in Yellow Zone	VPLH	6	Vulnerable people at risk in Yellow Zone	Eq. (3.1)
	Toxicity	Severity	0	Tailings is inert	Table 3.14
	Damage to Infrastructure and Facilities	Severity	2	Main roads and medical unit are both damaged	Table 3.14
	Quickness of rescue services	Severity	1	Rescue services is expected to reach in 30 minutes.	Table 3.14
	Resilience of Residents	Severity	2	Residences are mostly constructed with weak materials	Table 3.14
	Vulnerability to Natural Hazards	Severity	1	Region is vulnerable to natural floods	Table 3.14
	Emergency Planning	Degree of Preparedness	0	There is no emergency plan	Table 3.15
	First Aid Opportunities	Degree of Preparedness	2	Medical unit exists in affected area	Table 3.15
	Early Warning System	Degree of Preparedness	0	None	Table 3.15
	Training	Degree of Preparedness	0	None	Table 3.15
Social and Economic Life	Ws	Converter	0.55	Weight of Economic Support	Eq. (3.6)
	Traumatic Stress	Unrest	6	Loss of both active and vulnerable groups	Table 3.16
	Damage to Infrastructure	Unrest	6	Damage to roads, drinking water sources and power lines	Table 3.16
	Loss of Cultural Entities	Unrest	2	Damage to mosque	Table 3.16
	Population	Vulnerability	200	Total number of people living in community	Eq. (3.7)
	Forced Evacuation	Displacement	2	Dam site is prone to extreme hydraulic events	Table 3.17
	Loss of Houses	Displacement	3	40 % of houses damaged	Table 3.17
	Loss of Public Services	Displacement	3	Potential damage to medical service	Table 3.17
	Lost Land Use	Poverty	0.4	Ratio (40 % of total land is affected)	Eq. (3.15)
	Loss of Water Bodies	Poverty	1	All the waterbodies are affected	Eq. (3.16)
	Loss of Workplaces	Poverty	0	Ratio (None of workplaces is affected)	Eq. (3.17)
	Total number of labors	Poverty	120	Number of active people	Eq. (3.18)
	Unemployed People	Poverty	30	Number of people lost their work opportunities	Eq. (3.18)

Table 5.3 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam B
(cont'd)

Subsystem	Parameter	Factor	Value		Reference
Social and Economic Life	Dependency on Mining	Vulnerability	0.25	Ratio (25 % of total labor force works in mining)	Eq. (3.9)
	Diversity of Economic Activities	Vulnerability	0.25	1/4 (4 main activities in community)	Eq. (3.9)
	Proportion of Vulnerable Groups	Vulnerability	0.4	Ratio (40 % of population)	Eq. (3.9)
	Existence of Indigenous People	Vulnerability	0	None	Eq. (3.9)
	Donations	Economic Support	1	Expected donation by public	Table 3.18
	Compensation	Economic Support	2	Compensation could be provided both mine owner and government	Table 3.18
	Insurance	Economic Support	0	None	Table 3.18
Environment	Flood Ratio	Impact on Soil	0.4	Ratio (40 % of total area is flooded)	(3.24)
	Toxicity Soil	Danger to Soil	1	Tailings is non-toxic to soil	Table 3.19
	Intensity Soil	Danger to Soil	1	Contaminant source strength is expected to be decreasing significantly within a short time	Table 3.19
	Duration Soil	Danger to Soil	1	Pollution is expected to be temporary or short-lasting	Table 3.19
	Restoration Soil	Danger to Soil	1	Affected soil can be restored through minor clean-up and restoration efforts	Table 3.6
	Extinction Status Soil	Biodiversity	0	None	Table 3.20
	Endemism Status Soil	Biodiversity	0	None	Table 3.20
	Protection Status Soil	Biodiversity	0	None	Table 3.20
	Land Fertility	Non-aquatic Ecosystem Services	2	Loss of any income generating land	Table 3.21
	Pollination	Non-aquatic Ecosystem Services	2	Loss of lands covered by vegetation	Table 3.21
	Natural Products Soil	Non-aquatic Ecosystem Services	2	Loss of at least two natural products	Table 3.21
	Recreation Soil	Non-aquatic Ecosystem Services	1	Loss of lands having any recreational value	Table 3.20
	Extinction Status Water	Aquatic life	0	None	Table 3.21
	Endemism Status Water	Aquatic life	0	None	Table 3.23

Table 5.3 Hypothetical Consequence Dataset for the Model Implementation for Tailings Dam B
(cont'd)

Subsystem	Parameter	Factor	Value		Reference
Environment	Protection Status Water	Aquatic life	0	None	Table 3.23
	Toxicity Water	Danger to Water	2	Tailings contains toxic substances to water body	Table 3.23
	Intensity Water	Danger to Water	2	Contaminant source strength is expected to be decreasing within a prolonged time	Table 3.22
	Duration Water	Danger to Water	2	Pollution is expected to be permanent or long-lasting	Table 3.22
	Restoration Water	Danger to Water	2	Affected water bodies can be restored through major clean-up and restoration efforts	Table 3.22
	Drinking Water	Aquatic Ecosystem Services	2	Water body provides drinking water	Table 3.24
	Irrigation	Aquatic Ecosystem Services	2	Lands are irrigated using the water body.	Table 3.24
	Aquatic Natural Products	Aquatic Ecosystem Services	2	Loss of any natural product with an economic importance	Table 3.24
	Recreation Water	Aquatic Ecosystem Services	1	Affected water body having any recreational value	Table 3.24

Table 5.4 Hypothetical Failure Potential Dataset for the Model Implementation for Tailings Dam B

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Abandoned Dam (AD) Failure Potential	W _a (Management Ratio)	Abandoned Dam Failure Potential	0.66	Weighting (66 %)	Eq. 3.50
	Extreme hydraulic events	AD Overtopping	2	Site is prone to high snowmelt	Table 3.38
	Natural hazard	AD Overtopping	2	Site is prone to avalanche	Table 3.38
	Flood control measures	AD Overtopping	4	Diversion channels or dikes with unknown design	Table 3.38
	Seismicity design	AD Slope Instability	4	PGA<0.20g with unknown closure design	Table 3.39
	Construction material	AD Slope Instability	6	Tailings or unknown	Table 3.39
	Seepage and drainage measures	AD Slope Instability	4	Measures with unknown design	Table 3.39
	Height and inclination	AD Slope Instability	4	10 to 30 m and >27°	Table 3.39
	Erosion measures	AD Slope Instability	3	Dam walls are covered with any protective cover	Table 3.39
	SI Abandoned Dam type	AD Slope Instability	6	Upstream dam	Table 3.39
	Phreatic surface control	AD Internal Erosion	6	No control measures	Table 3.40

Table 5.4 Hypothetical Failure Potential Dataset for the Model Implementation for TDB (cont'd)

Subsystem	Parameter	Factor	Value	Data or Impact	Ref. Table or Equation
Abandoned Dam (AD) Failure Potential	IE Abandoned Dam type	AD Internal Erosion	6	Upstream dam	Table 3.40
	Foundation properties	AD Foundation Failure	3	Cracked or fractured rocks	Table 3.41
	Groundwater condition	AD Foundation Failure	3	Sited on shallow unsaturated zone	Table 3.41
	Subsidence measure	AD Foundation Failure	4	Sited on karstic formation	Table 3.41
	Seismicity measure	AD Foundation Failure	2	PGA < 0.20g	Table 3.41
	Seepage measure	AD Foundation Failure	4	Measures with unknown design	Table 3.41
	F Abandoned Dam type	AD Foundation Failure	6	Upstream dam	Table 3.41
	Monitoring and warning system	AD Management Factor	3	Monitoring on request	Table 3.42
	Regulatory control	AD Management Factor	3	Irregular or on-requested control	Table 3.42
	Dam behavior	AD Management Factor	4	Dam had any incident that required technical inspection	Table 3.42
	AD Overtopping Weighting Factor	AD Failure Mode	0.19	Weighting (19 %)	Eq. (3.54)
	AD Slope Instability Weighting Factor	AD Failure Mode	0.33	Weighting (33 %)	Eq. (3.54)
	AD Internal Erosion Weighting Factor	AD Failure Mode	0.21	Weighting (21 %)	Eq. (3.54)
	AD Foundation Weighting Factor	AD Failure Mode	0.27	Weighting (27 %)	Eq. (3.54)

5.1.3 Model Results

The model calculates the combined risk from Tailings Dam A and Tailings Dam B at the end of 10 years as 30.2 (see Figure 5.2). Risk scores increase from 19.2 to 30.2 in ten years. After the year-7, the trend of risk scores notably changes and increases because the tailings flows reach the residential area and potential fatalities occur after this year (see Figure 5.1).

Risk scores from Tailings Dam A only, and Tailings Dam B only are shown in Figure 5.3 and Figure 5.4, respectively. If Tailings Dam A exists upstream only, the risk value is computed as 9.97, where as in case of Tailings Dam B only, the risk value

is 14.6. It means that the concerned community faces a “significant” risk from Tailings Dam A according to risk classification proposed in this thesis (see Table 3.44). In case of Tailings Dam B failure, community is under the threat of “High” risk. However, combined risk induced by Tailings Dam A and Tailings Dam B reveals that the community confronts “Serious” risk.

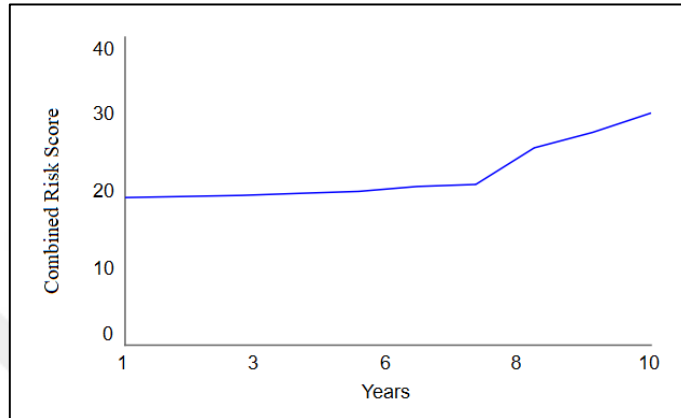


Figure 5.2: Variation of Combined Risk in Time

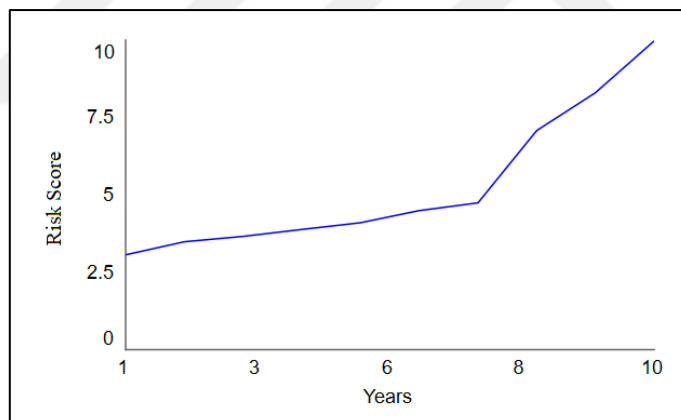


Figure 5.3: Variation of Risk from Tailings Dam A in Time

The model results show that until the eight year of the simulation, Tailings Dam A poses a threat classified as “negligible” risk. During the same time interval, the downstream community is at a risk classified as “High” from Tailings Dam B. The combined risk model takes the highest of the risks from the individual tailings dams during this time period, indicating that the community is at “High” risk.

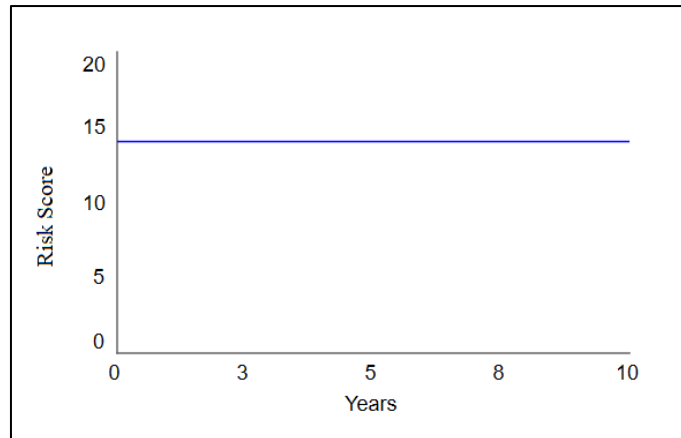


Figure 5.4: Variation of Risk from Tailings Dam B in Time

5.2 Validation of the Developed Model by a Real Case

Developed system dynamics model was validated using Stava disaster occurred in 1985 in Italy, which involved the collapse of two tailings dams holding mining waste from a nearby fluorite mine. The collapse released a massive mudflow that swept through the valley, destroying the village of Stava and killing many people. The Stava disaster remains one of the worst mining disasters in European history (Luino and De Graff, 2012). Since the failure event involves multiple tailings dams, and its causes and consequences are relatively well documented, it is a good candidate to implement the developed model.

5.2.1 Risk Body and Event

The Stava Creek, with a drainage area of approximately 21 km², is located in the Dolomite Mountains, North-Eastern Italy, in the upper valley of the Avisio River. On July 19, 1985, two tailings dams collapsed at Stava near Tesero (Italian Alps), resulting in the tragic loss of many lives and widespread destruction. The collapse of the upper tailings dam triggered a devastating mudflow that cascaded down the Stava valley, overwhelming the lower tailings dam and destroying the village of Stava and parts of Tesero (See Figure 5.5). Although the tailings flow resulted in impacts

through the course of Stava Creek down to Avisio River, chosen Risk Body only covers Stava Village with its surrounding environment (See Figure 5.6). Impacts on the outside of risk body were excluded in the risk assessment.



Figure 5.5 Graphic reconstruction of the area impacted by the tailings flow and risk body of the model (reproduced from Sammarco, 2004)



Figure 5.6: Before and after shots in the village of Tesero (in Luino and De Graff, 2012)

Collapsed impoundments were designed to store fine-grained waste material (tailings) from a nearby fluorite mine. When failure occurred, the lower dam was 25 m high and the upper dam was over 34 m high. Together, they made up an earth structure nearly 60 m high. The upper dam had a berm at about 2/3 from its base, which partially rested on the silt of the lower dam. The upper dam's slope was about 38° below the berm and about 32° above the berm (Simeoni et. al. 2017).



Figure 5.7: Stava tailings dams before failure (in Luino and De Graff, 2012)

Mudflow caused the death of 268 people (including 59 under-18s), the complete destruction of 3 hotels, 53 houses, 6 sheds and hundreds of trees. In addition, 8 bridges and 9 heavily damaged buildings were demolished. A layer of mud between 20 and 40 cm thick covered an area of approximately $435\,000\text{ m}^2$ for a length of 4.2 km (Roche et. al, 2017). Location of the Stava tailings dams with reconstruction of the area impacted by the 1985 flowing event (shadowed area) is shown in Figure 5.8 (Pirulli et. al. 2017).

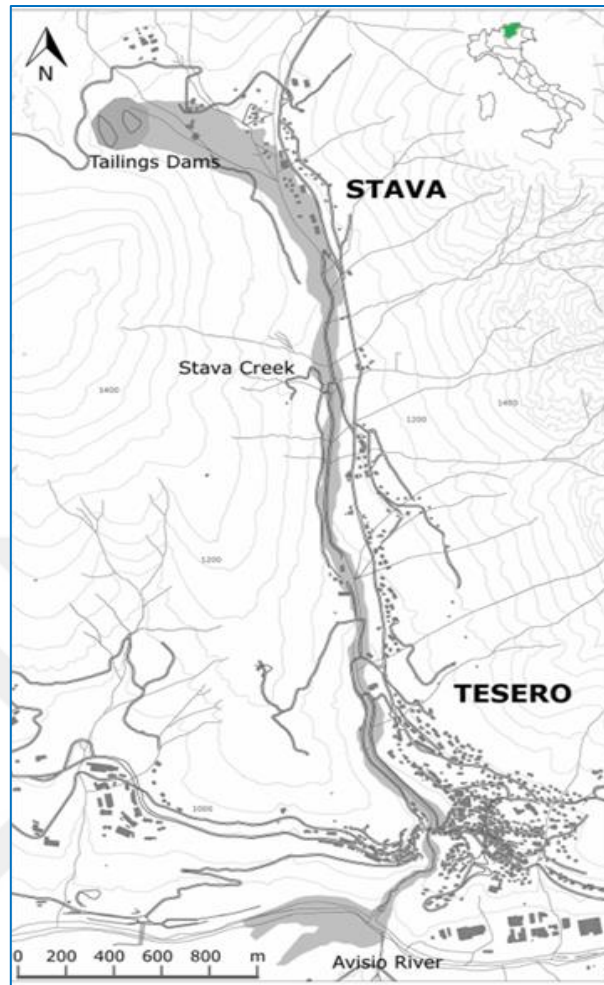


Figure 5.8: Location of the Stava tailings dams with reconstruction of the area impacted by the 1985 flowing event (shadowed area) (in Pirulli et. al. 2017)

5.2.2 Case 1: Lower Dam Collapse

The approach followed in this case is to determine whether the disaster could have been predicted if a risk assessment had been made for the lower dam before the upper dam was built.

Model Input

Stava Village is chosen as a risk body (see Figure 5.5), hence impacts of the event on Tesero are excluded in the model. Although Stava Tailings Dam collapse is famous among this type of disasters and relatively well documented, it must be

acknowledged that direct, comprehensive pre-disaster data or surveys specifically for Stava village in 1985 are not explicitly provided within the available literature and internet sources. Consequently, the information about pre-event conditions of Stava is based on post-disaster impact assessments, descriptions of the catastrophe's effects, and the historical context of the valley's development. It should be also noted that population of Stava on the day of the disaster was not solely its permanent residents but a much larger, more diverse group from outside the Stava Village. This suggests that the community's effective population on the day of the disaster was substantially augmented by tourism. Therefore, population of Stava at risk is estimated by the number of houses damaged.

In order to determine the flooded area, flow velocities and depth of flooded tailings HEC-RAS model was utilised. It is widely used to simulate the potential breach of a tailings dam and the subsequent propagation of the released material (which can be a mixture of water and tailings, often behaving as a non-Newtonian fluid like a mudflow or hyper-concentrated flow).

The embankment of the upper dam failed, causing the collapse of the lower one as well. This released a mass of about 180 000 m³ of water and mud pouring at a speed of about 90 km/h in the valley below. Runout material is approximated for the lower dam using Figure 5.9 and 1/4 of total material (45 hm³) is assigned to lower dam as runout material.

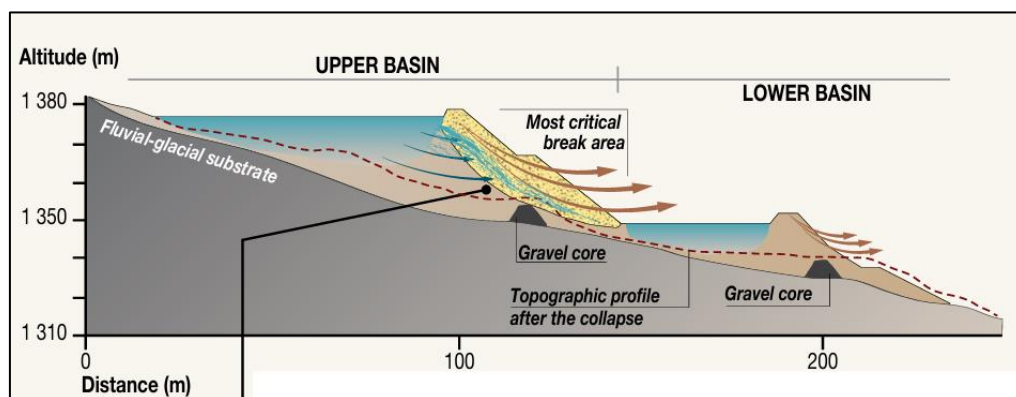


Figure 5.9: Profiles of upper and lower dams (in Roche et. al, 2017)

Inundation area in case of upper dam failure event and lower dam only failure event obtained by flow model is shown in Figure 5.10 and Figure 5.11, respectively. Comparison of the modelled inundation area with the reconstruction of the area impacted by the 1985 flowing event by Piruli *et. al.* (2017) (see Figure 5.8) reveals that the model gives a good approximation for inundation (coverage) area for Stava Village. As far as flow velocities and flow depths are concerned, flow depth profiles of both events shown in Figure 5.12 and Figure 5.13 reveals that flows almost always has a depth of greater than 0.7 meter. Therefore, consequence of the lower dam collapse is assessed only within Red Zone and consequences in Yellow Zone (flow depth < 0.7 m) are neglected. From the graphic reconstructions of flooded area (Roche *et. al.*, 2017; Sammarco, 2004), 21 out of 45 buildings were determined to be damaged. Although the types of buildings were not indicated, 3 sheds, 2 hotels, 12 houses and 4 other buildings were assumed to be damaged in the risk body (Stava Village). Since among 268 fatalities the number of people under-18s is 59, which is 22% of total deaths, the proportion of the vulnerable people at risk is assumed to be 40 % adding 18% allowance for the elderly.

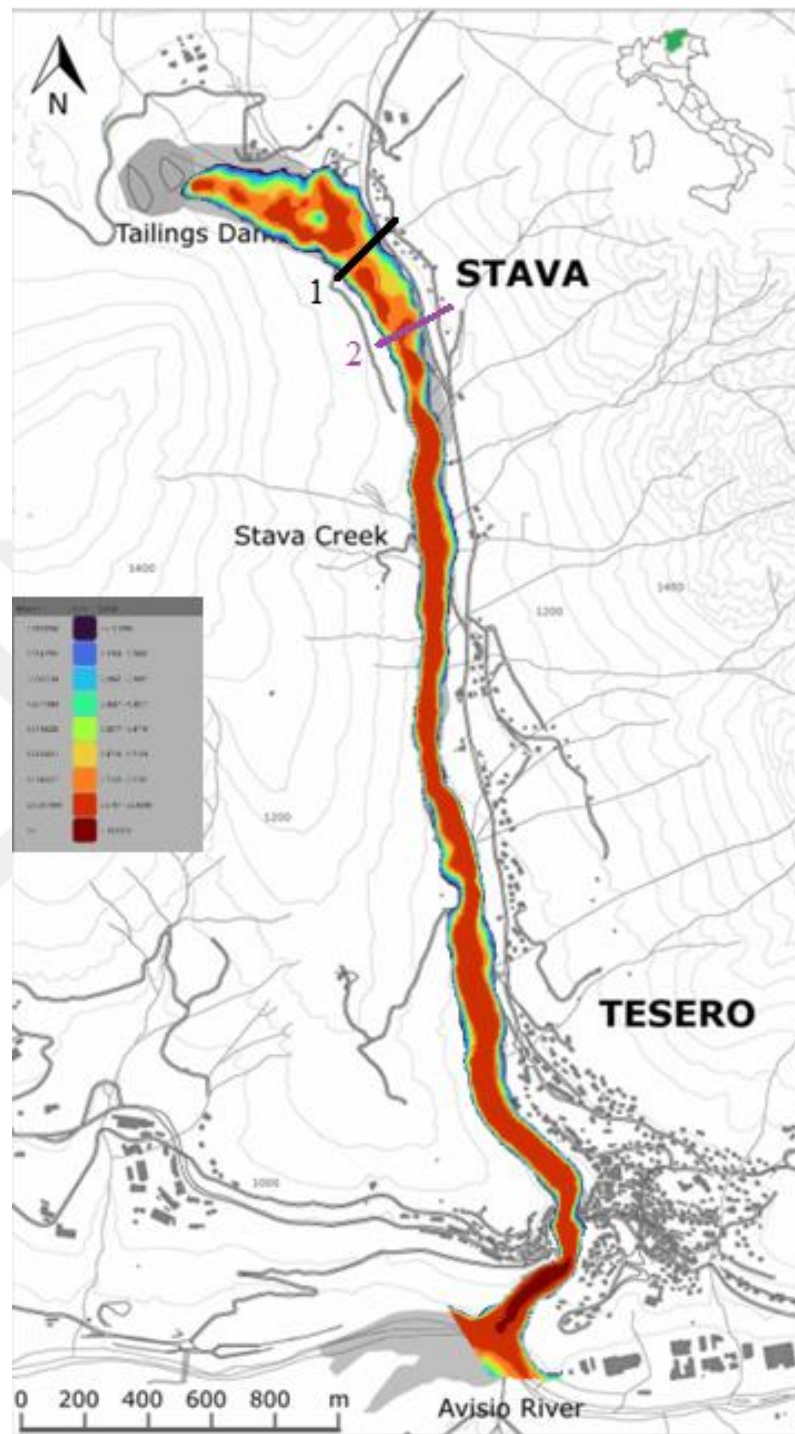


Figure 5.10: Flow model result for inundation area of Upper Dam collapse event reproduced from Pirulli *et. al.* 2017

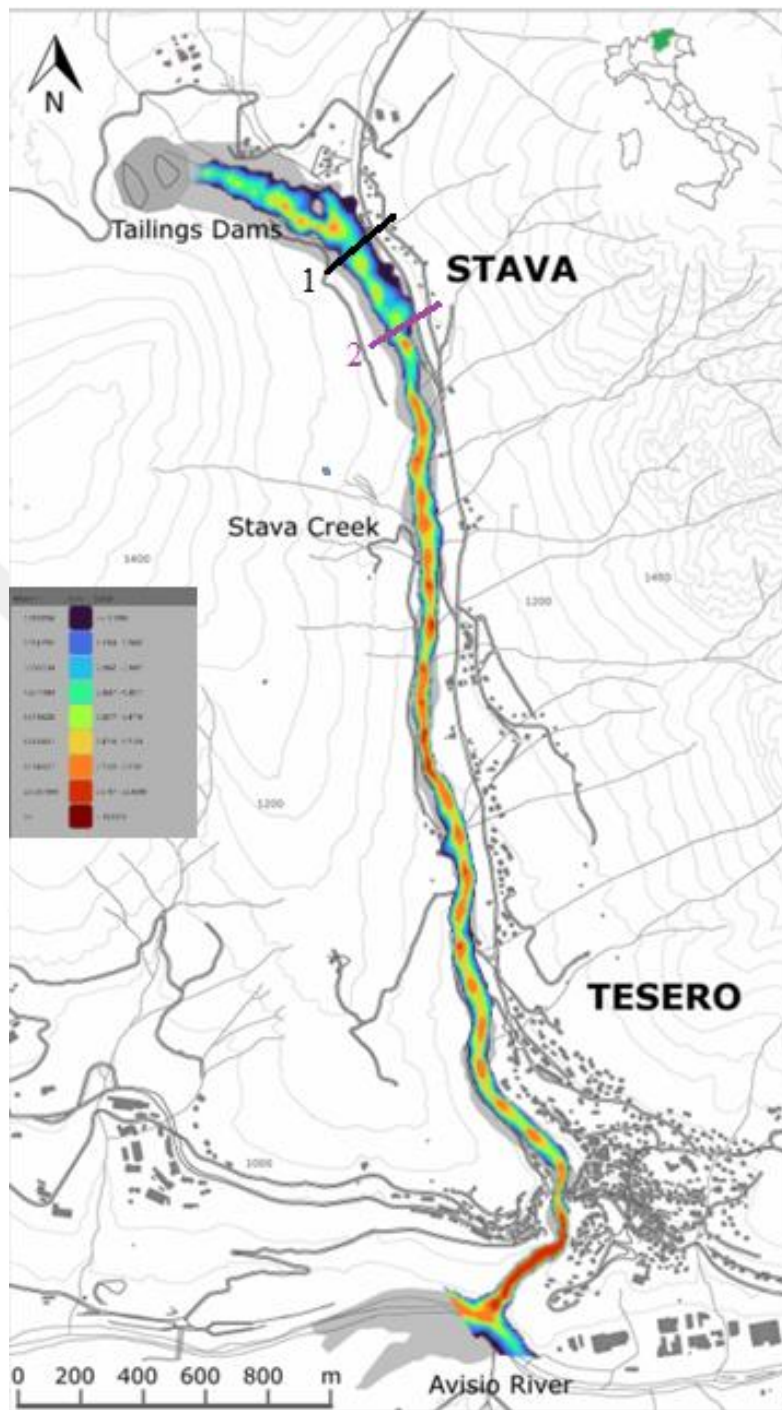


Figure 5.11: Flow model result for inundation area of Lower Dam collapse only event reproduced from Pirulli *et. al.* 2017

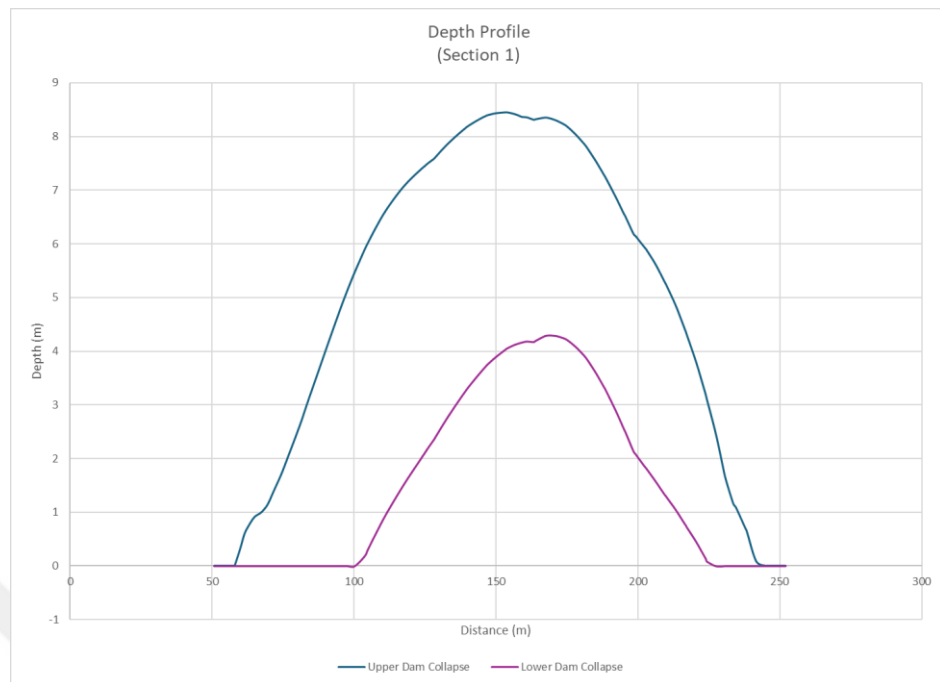


Figure 5.12 Velocity Profiles of the Events

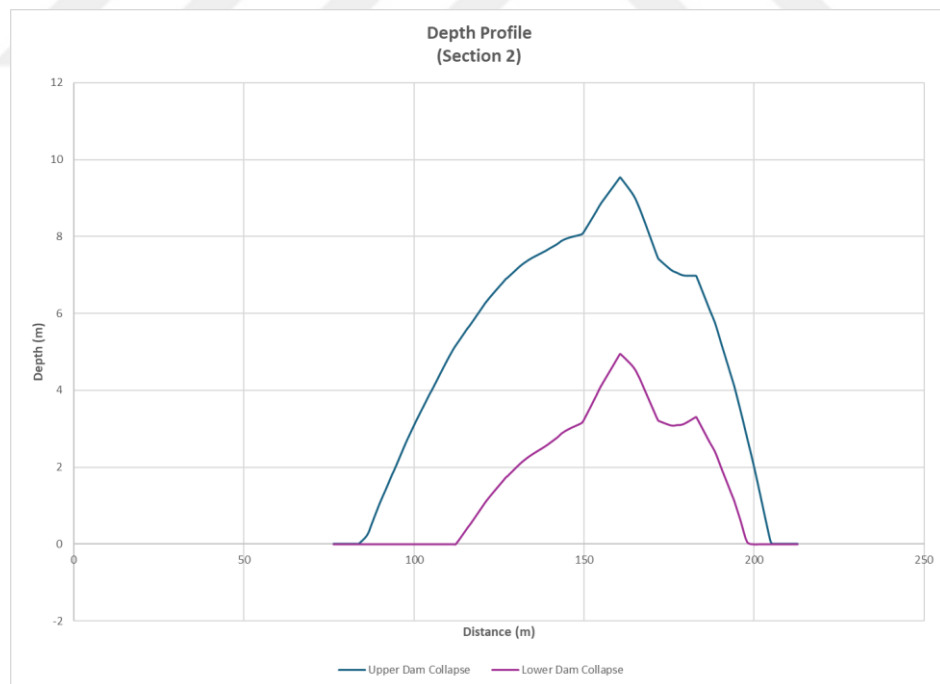


Figure 5.13 Flow Depth Profiles of Events

Datasets for the consequence assessment and failure potential for Lower Dam are given in Table 5.5 and Table 5.6. All the values are estimated using available data from literature given above and Google Earth satellite views.

Table 5.5 Consequence Dataset for the Model Implementation for Lower Dam

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Human Health	APAR in RED Zone	APLL	29	12 houses, 4 people per house, 60 % of population
	VPAR in Red Zone	VPLL	19	40 % of 48 people
	APAR in Yellow Zone	APLH	0	No Yellow Zone
	VPAR in Yellow Zone	VPLH	0	No Yellow Zone
	Toxicity	Severity Factor	1	Tailings containing substances causing chronic health problems
	Damage to Infrastructure and Facilities	Severity Factor	2	Main roads are damaged and there is no medical unit
	Quickness of rescue services	Severity Factor	1	≥ 18 minutes
	Resilience of Residents	Severity Factor	2	Residences are mostly constructed with weak materials
	Vulnerability to Natural Hazards	Severity Factor	1	Vulnerable to natural floods
	Emergency Planning	Degree of Preparedness	0	None
	First Aid Opportunities	Degree of Preparedness	0	None
	Early Warning System	Degree of Preparedness	0	None
	Training	Degree of Preparedness	0	None
Social and Economic Life	Ws	Social and Economic Impact	0.55	
	Traumatic Stress	Unrest	6	Loss of active and vulnerable groups
	Damage to Infrastructure	Unrest	6	Roads, drinking water infrastructure, power and communication lines
	Loss of Cultural Entities	Unrest	3	Loss of places of worship
	Population	Vulnerability	144	36 houses, 4 people per houses
	Forced Evacuation	Displacement	2	Dam site is prone to extreme hydraulic events
	Loss of Houses	Displacement	1	33 % (12/36)
	Loss of Public Services	Displacement	0	None
	Loss of Land Use	Poverty	0.3	30 % of land use
	Loss of Water Bodies	Poverty	1	Stava River
	Loss of Workplaces	Poverty	0.5	50 % (loss of hotels and other buildings)
	Total number of labors	Poverty	86	
	Unemployed People	Poverty	16	

Table 5.5 Consequence Dataset for the Model Implementation for Lower Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Social and Economic Life	Dependency on Mining	Vulnerability	0.1	8 miners
	Diversity of Economic Activities	Vulnerability	1	Main activity is tourism
	Proportion of Vulnerable Groups	Vulnerability	0.4	40 % Population
	Existence of Indigenous People	Vulnerability	0	None
	Donations	Economic Support	1	Expected donation by public
	Compensation	Economic Support	1	Expected compensation by mine owner
	Insurance	Economic Support	0	None
Environment	Flood Ratio	Impact on Soil	0.12	6 hectares out of 50 hectares flooded area
	Toxicity Soil	Danger to Soil	1	Tailings is non-toxic to soil
	Intensity Soil	Danger to Soil	1	Contaminant source strength is expected to be decreasing significantly within a short time
	Duration Soil	Danger to Soil	2	Pollution is expected to be long-lasting
	Restoration Soil	Danger to Soil	2	Affected soil can be restored through major clean-up and restoration efforts
	Extinction Status Soil	Index for Biodiversity	0	None
	Endemism Status Soil	Index for Biodiversity	1	Affected lands habituating regional endemic or widely spread species (Italian Alps)
	Protection Status Soil	Index for Biodiversity	0	None
	Land Fertility	Non-aquatic Ecosystem Services	2	Loss of any income-generating land (Farmland)
	Pollination	Non-aquatic Ecosystem Services	2	Loss of lands covered by vegetation
	Natural Products Soil	Non-aquatic Ecosystem Services	1	Loss of any natural products
	Recreation Soil	Non-aquatic Ecosystem Services	2	Loss of lands having significant recreational value
	Extinction Status Water	Index for aquatic life	0	None
	Endemism Status Water	Index for aquatic life	1	Water bodies habituating regional endemic or widely spread species
	Protection Status Water	Index for aquatic life	1	None
	Toxicity Water	Danger to Water	2	Tailings contains toxic substances to water body
	Intensity Water	Danger to Water	1	Contaminant source strength is expected to be decreasing significantly within a short time
	Duration Water	Danger to Water	1	Pollution is expected to be temporary

Table 5.5 Consequence Dataset for the Model Implementation for Lower Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Environment	Restoration Water	Danger to Water	2	Affected water bodies can be restored through minor clean-up and restoration efforts
	Drinking Water	Aquatic Ecosystem Services	1	Water body does not provide drinking water.
	Irrigation	Aquatic Ecosystem Services	1	Water body does not provide irrigation water.
	Aquatic Natural Products	Aquatic Ecosystem Services	1	Loss of natural product (fish)
	Recreation Water	Aquatic Ecosystem Services	2	Affected water body having significant recreational value

Table 5.6 Failure Potential Dataset for the Model Implementation for Lower Dam

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Abandoned Dam (AD) Failure Potential	W _a (Management Ratio)	Abandoned Dam Failure Potential	0.66	Expert Evaluation
	Extreme hydraulic events	AD Overtopping	4	Site is prone to high intensity rains and snowmelts (Italian Alps)
	Natural hazard	AD Overtopping	4	Site is prone to landslide and avalanche
	Flood control measures	AD Overtopping	6	None
	Seismicity design	AD Slope Instability	4	PGA<0.20g with unknown closure design
	Construction material	AD Slope Instability	6	Tailings or unknown
	Seepage and drainage measures	AD Slope Instability	4	Measures with any design
	Height and inclination	AD Slope Instability	4	> 10 m and >27°
	Erosion measures	AD Slope Instability	6	Dam is constructed with unknown fill or tailings itself without cover
	SI Abandoned Dam type	AD Slope Instability	6	Upstream type
	Phreatic surface control	AD Internal Erosion	6	No control
	IE Abandoned Dam type	AD Internal Erosion	6	Upstream type
	Foundation properties	AD Foundation Failure	6	Weak soils
	Groundwater condition	AD Foundation Failure	6	Sited on saturated zone
	Subsidence measure	AD Foundation Failure	0	None
	Seismicity measure	AD Foundation Failure	2	PGA < 0.20g
	Seepage measure	AD Foundation Failure	4	Measures with any design

Table 5.6 Failure Potential Dataset for the Model Implementation for Lower Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Abandoned Dam (AD) Failure Potential	F Abandoned Dam type	AD Foundation Failure	6	Upstream type
	Monitoring and warning system	AD Management Factor	0	None
	Regulatory control	AD Management Factor	3	Irregular or on-requested control
	Dam behavior	AD Management Factor	3	Dam had any incident that required technical inspection
	AD Overtopping Weighting Factor	AD Failure Mode	0.19	Expert Evaluation
	AD Slope Instability Weighting Factor	AD Failure Mode	0.33	Expert Evaluation
	AD Internal Erosion Weighting Factor	AD Failure Mode	0.21	Expert Evaluation
	AD Foundation Weighting Factor	AD Failure Mode	0.27	Expert Evaluation

Results

The model calculates the risk from Stava Lower Dam as 25.1. It means that the Stava Village faces a “serious” risk from Lower Dam only event according to risk classification proposed in this thesis (see Table 3.44). As to failure potential of the dam, Lower Dam has a score of 4.82. It corresponds to “Very High” failure potential class which means that the dam has hidden serious problems and need urgent treatment. Consequence score value of Lower Dam is found to be 5.19 which corresponds to “Significant” class. Consequence score value indicates that in case of a failure event Stava Valley would have faced severe consequences.

5.2.3 Case 2: Upper Dam Collapse

Aim of this case study is to predict how much the risk increased when Upper Dam was built using the risk model proposed in this thesis study. The followed approach is whether increased risk levels could have been predicted if a combined risk assessment had been made for the Upper Dam in the early months of 1985.

Datasets for the consequence assessment and the failure potential for Upper Dam are given in Table 5.7 and Table 5.8. All the values are estimated using available data from literature given above and graphical reconstructions of impacted area.

Upon Upper Dam collapsed, from the graphic reconstructions of flooded area (Roche et. al, 2017; Sammarco, 2004), 32 out of 45 buildings were estimated to be damaged. In this particular instance 3 sheds, 2 hotels, 21 houses and 4 other buildings were assumed to be damaged in Stava Village (Risk Body). The proportion of the vulnerable people at risk is assumed to be 40 % as in the case of Lower Dam collapse.

Table 5.7 Consequence Dataset for the Model Implementation for Upper Dam

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Human Health	APAR in RED Zone	APLL	55	23 houses, 4 people per house, 60 % of population
	VPAR in Red Zone	VPLL	37	40 % of 92 people
	APAR in Yellow Zone	APLH	0	No Yellow Zone
	VPAR in Yellow Zone	VPLH	0	No Yellow Zone
	Toxicity	Severity Factor	1	Tailings containing substances causing chronic health problems
	Damage to Infrastructure and Facilities	Severity Factor	2	Main roads are damaged and there is no medical unit
	Quickness of rescue services	Severity Factor	1	≥ 18 minutes
	Resilience of Residents	Severity Factor	2	Residences are mostly constructed with weak materials
	Vulnerability to Natural Hazards	Severity Factor	1	Vulnerable to natural floods
	Emergency Planning	Degree of Preparedness	0	None
	First Aid Opportunities	Degree of Preparedness	0	None
	Early Warning System	Degree of Preparedness	0	None
	Training	Degree of Preparedness	0	None
Social and Economic Life	Ws	Social and Economic Impact	0.55	
	Traumatic Stress	Unrest	6	Loss of active and vulnerable groups
	Damage to Infrastructure	Unrest	6	Roads, drinking water infrastructure, power and communication lines
	Loss of Cultural Entities	Unrest	3	Loss of places of worship
	Population	Vulnerability	144	36 houses, 4 people per houses
	Forced Evacuation	Displacement	2	Dam site is prone to extreme hydraulic events
	Loss of Houses	Displacement	3	63 % (23/36)

Table 5.7 Consequence Dataset for the Model Implementation for Upper Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
	Loss of Public Services	Displacement	0	None
	Loss of Land Use	Poverty	0.4	40 % of land use
	Loss of Water Bodies	Poverty	1	Stava River
	Loss of Workplaces	Poverty	0.5	50 % (loss of hotels and other buildings)
	Total number of labors	Poverty	86	
	Unemployed People	Poverty	16	
	Dependency on Mining	Vulnerability	0.1	8 miners
	Diversity of Economic Activities	Vulnerability	1	Main activity is tourism
	Proportion of Vulnerable Groups	Vulnerability	0.4	40 % Population
	Existence of Indigenous People	Vulnerability	0	None
	Donations	Economic Support	1	Expected donation by public
	Compensation	Economic Support	1	Expected compensation by mine owner
	Insurance	Economic Support	0	None
	Flood Ratio	Impact on Soil	0.24	12 hectares out of 50 hectares flooded area
	Toxicity Soil	Danger to Soil	1	Tailings is non-toxic to soil
	Intensity Soil	Danger to Soil	1	Contaminant source strength is expected to be decreasing significantly within a short time
	Duration Soil	Danger to Soil	2	Pollution is expected to be long-lasting
Environment	Restoration Soil	Danger to Soil	2	Affected soil can be restored through major clean-up and restoration efforts
	Extinction Status Soil	Index for Biodiversity	0	None
	Endemism Status Soil	Index for Biodiversity	1	Affected lands habituating regional endemic or widely spread species (Italian Alps)
	Protection Status Soil	Index for Biodiversity	0	None
	Land Fertility	Non-aquatic Ecosystem Services	2	Loss of any income-generating land (Farmland)
	Pollination	Non-aquatic Ecosystem Services	2	Loss of lands covered by vegetation
	Natural Products Soil	Non-aquatic Ecosystem Services	1	Loss of any natural products
	Recreation Soil	Non-aquatic Ecosystem Services	2	Loss of lands having significant recreational value

Table 5.7 Consequence Dataset for the Model Implementation for Upper Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Environment	Extinction Status Water	Index for aquatic life	0	None
	Endemism Status Water	Index for aquatic life	1	Water bodies habituating regional endemic or widely spread species
	Protection Status Water	Index for aquatic life	1	None
	Toxicity Water	Danger to Water	2	Tailings contains toxic substances to water body
	Intensity Water	Danger to Water	1	Contaminant source strength is expected to be decreasing significantly within a short time
	Duration Water	Danger to Water	1	Pollution is expected to be temporary
	Restoration Water	Danger to Water	2	Affected water bodies can be restored through minor clean-up and restoration efforts
	Drinking Water	Aquatic Ecosystem Services	1	Water body does not provide drinking water.
	Irrigation	Aquatic Ecosystem Services	1	Water body does not provide irrigation water.
	Aquatic Natural Products	Aquatic Ecosystem Services	1	Loss of natural product (fish)
	Recreation Water	Aquatic Ecosystem Services	2	Affected water body having significant recreational value

Table 5.8 Failure Potential Dataset for the Model Implementation for Upper Dam

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Abandoned Dam (AD) Failure Potential	W _a (Management Ratio)	Abandoned Dam Failure Potential	0.66	Expert Evaluation
	Extreme hydraulic events	AD Overtopping	4	Site is prone to high intensity rains and snowmelts (Italian Alps)
	Natural hazard	AD Overtopping	4	Site is prone to landslide and avalanche
	Flood control measures	AD Overtopping	6	None
	Seismicity design	AD Slope Instability	4	PGA<0.20g with unknown closure design
	Construction material	AD Slope Instability	6	Tailings or unknown
	Seepage and drainage measures	AD Slope Instability	6	Sign of seepage
	Height and inclination	AD Slope Instability	6	> 30 m and >27°

Table 5.8 Failure Potential Dataset for the Model Implementation for Upper Dam (cont'd)

Subsystem	Parameter	Factor	Value	Data/Estimate Source
Abandoned Dam (AD) Failure Potential	Erosion measures	AD Slope Instability	6	Dam is constructed with unknown fill or tailings itself without cover
	SI Abandoned Dam type	AD Slope Instability	6	Upstream type
	Phreatic surface control	AD Internal Erosion	6	No control
	IE Abandoned Dam type	AD Internal Erosion	6	Upstream type
	Foundation properties	AD Foundation Failure	6	Weak soils
	Groundwater condition	AD Foundation Failure	6	Sited on saturated zone
	Subsidence measure	AD Foundation Failure	0	None
	Seismicity measure	AD Foundation Failure	2	PGA < 0.20g
	Seepage measure	AD Foundation Failure	4	Measures with any design
	F Abandoned Dam type	AD Foundation Failure	6	Upstream type
	Monitoring and warning system	AD Management Factor	0	None
	Regulatory control	AD Management Factor	3	Irregular or on-requested control
	Dam behavior	AD Management Factor	0	Dam had any incident that required maintenance
	AD Overtopping Weighting Factor	AD Failure Mode	0.19	Expert Evaluation
	AD Slope Instability Weighting Factor	AD Failure Mode	0.33	Expert Evaluation
	AD Internal Erosion Weighting Factor	AD Failure Mode	0.21	Expert Evaluation
	AD Foundation Weighting Factor	AD Failure Mode	0.27	Expert Evaluation

The model calculates the risk of Stava Village from collapse of Upper Dam as 32.6 which means that the risk body faces a “extreme” risk from the event (see Table 3.44). As to failure potential of the dam, Upper Dam has a score of 5.72 which corresponds to “extreme” failure potential class. It means that the dam will evidently collapse at any time. Consequence score value of Upper Dam is found to be 5.69

which corresponds to “Serious” class. Consequence score value indicates that in case of a failure event Stava Village will face massive consequences.

The model calculates the combined risk score of Stava Village as 46.1 which is far beyond the lower limit of extreme class. Combined risk assessment shows that existence of Upper Dam under stated conditions would evidently result in the occurrence of a disaster.

Combined risk assessment proposed in this thesis study demonstrates the fundamental error was the initial site selection without proper investigation, driven by economic expediency. The disaster could have been prevented at the earliest stage: site selection and initial design. A robust risk assessment framework must therefore begin with a "no-go" principle for unsuitable sites, even if economically attractive, and prioritize comprehensive baseline data collection over cost-cutting. Construction of multiple tailings dam upstream of communities will eventually increase the risks possibly beyond acceptable levels. Combined risk assessment helps to ensure that site selections accounts risks from multiple sources and designs incorporate conservative safety factors to protect downstream communities from destructive impacts.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Tailings dams have failed at a rate significantly higher than the failure rate for water supply dams resulting in serious treats to societies. Recent dam incidents serve as a critical reminder of the catastrophic consequences that can result from the failure of tailings dams, particularly when multiple structures are involved, such as Stava disaster (Italy) in 1985. The loss of life and widespread destruction caused by the collapse of the two tailings dams in Stava highlights the vulnerability of these systems and the need for proactive measures to mitigate risks.

Risk assessment processes for tailings dams typically focus on the risks associated with individual facilities. This approach is often valid when a single mine operation is located in a remote area. However, when multiple tailings dams are situated close to communities, the combined risks must be considered. The proposed thesis aims to develop a method for assessing the combined risk associated with multiple tailings dams within a shared watershed.

In this context, the thesis presents a methodology for evaluating the combined risks caused by multiple tailings dams located upstream of a community. The first step involves the development of a conceptual risk assessment model that includes three primary consequence evaluation subsystems: human health, social and economic impacts, and environmental effects. Additionally, two failure potential evaluation subsystems are incorporated to assess the potential of dam failure during both their active and inactive lifetimes. Due to the diverse, complex, dynamic, and

interdependent nature of failure mechanisms and the resulting impacts from tailings dam breaches or collapses, the conceptual model is subsequently translated into a system dynamics model. The developed system dynamics model is then applied to a hypothetical dataset involving two dams, one active and one inactive, that share a common risk body. Results show a promising applicability of proposed combined risk model. Implementation of the risk assessment model to the real case of Stava tailing dam disaster in 1985 reveals that risk assessment plays an important role in secure production of mines and protection of communities.

6.2 Recommendations

Following recommendations can be considered to enhance the research findings for future studies in this area.

- Introducing time dependent values (time-series) as a function of time is critical in system dynamic model. Although the consequence model in this thesis utilizes some time dependent variables, it is assumed that the risk body remains unchanged during time frame of simulation. Incorporation of the variations of conditions within the risk body, such as population increase, will be good contribution to construct a more realistic assessment model.
- Failure potential model of this study for active dams is a dynamic model, where as other failure potential models are not time dependent being static. Addition of appropriate time variant exceedance probabilities to seismic and hydrologic variables or introducing impact of climate change will make the inactive life failure potential models more reliable.
- The studied model provides a single risk score using expected values for both individual and combined risk assessment. Instead, constants can be generated by random values from pre-determined distribution to produce a risk distribution.

- Despite the fact that this thesis study proposes a classification method for risks from single tailings dams and it is also used for the comparison of combined risk from multiple dams, a study to determine a specific classification system for combined risk is recommended.
- Combined risk model of this thesis study is appropriate for the cases which involves two or three tailings dam. When several tailings dams are involved risk assessment processes become more time consuming and need an overload effort, since application of flow models and scoring tasks gets harder to overcome.
- An adapted version of proposed model has a potential to be applied to heap leach sites and waste rock dumps, where similar threats and risks to the communities are valid.
- Combining System Dynamics modeling with research methods of social sciences can offer a deeper understanding of the human and organizational aspects influencing safety dynamics in tailings dam management.

By incorporating these recommendations, future studies can contribute to a more comprehensive understanding of the complex and dynamic interactions leading to catastrophic tailings dam failures. Further recommendation will be as follows.

The developed model in this thesis offers a promising tool for assessing the risk of tailings dam failures. It should be applied not only to historical cases but also to current and future tailings dams. By simulating potential failure scenarios, the model can help identify high risk dams and guide preventive measures. Authorities and mining companies should adopt such models as part of their risk management strategies.

Governments and regulatory bodies must establish and enforce stringent safety standards for tailings dam design, construction, and operation. These regulations should mandate comprehensive risk assessments, including the potential for

cascading failures when multiple dams are involved, and the implementation of fail-safe mechanisms to prevent such events.

Long term solutions to the risks associated with tailings dams involve improving the methods used for the disposal of mining waste. Research should focus on developing safer, more sustainable alternatives to traditional tailings storage methods, such as dry stacking or the use of more stable materials for dam construction. These innovations could reduce the environmental and human risks associated with tailings dams.



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APPENDIX A

QUESTIONNAIRE OF THE TSF FAILURE POTENTIAL SURVEY

Table A. 1: Questionnaire on Background Information of Participant in the Failure Potential Survey

QS	Code	Parameter	Question
Background	Q.1.1	-	Name and Surname
	Q.1.2	-	Age
	Q.1.3	-	Educational Level
	Q.1.4	-	What is your experience in the impact assessment, design, construction, operation, inspection, or related areas of tailings dams?
	Q.1.5	-	In the questions on the following pages, the potential social and economic impacts on a community in the event of a tailings dam failure will be assessed using both qualitative (linguistic) descriptions and quantitative (numerical) values. The meaning of qualitative terms can vary from person to person. Please define the minimum, average (expected), and maximum values on a scale of 1 to 10 for the qualitative descriptors: Very High, High, Medium, Low, Very Low Example: One person may define the term “high” as having a value between 7 (minimum) and 9 (maximum), with an average of around 8, while another may define it as ranging from 6 (minimum) to 9 (maximum), with an average of 7.

Table A. 2: Questionnaire on Active Dam Failure Modes in the Failure Potential Survey

QS	Code	Parameter	Question
Overtopping	Q.2.1	Extreme hydraulic events	Extreme hydraulic (meteorological) events such as tropical rainfall, heavy snowmelt or hurricanes in the area where the tailings dam is built are expected to have an impact on tailings dam overtopping. Accordingly, to what extent does extreme hydraulic events affect the overtopping of a tailings dam?
	Q.2.2	Natural hazards	Natural disasters such as landslides, avalanches or strong winds (cyclones) in the area where the tailings dam is built are expected to have an impact on the overtopping of the tailings dam. To what extent does natural disasters affect the overtopping of a tailings dam?
	Q.2.3	Excess water storage	In the design and operation of a tailings dam, it is expected that reserving a storage volume in the reservoir for excess water that may be filled by rainfall and/or catchment runoff will have an impact on tailings dam overtopping. To what extent does reserving an excess storage volume affect the overtopping of a tailings dam?
	Q.2.4	Flood control facilities	The construction of flood control structures, such as diversion channels for flows from the catchment of the tailings dam, or weir structures to discharge flood waters from the reservoir, are expected to affect the overtopping of the tailings dam. To what extent does flood control or weir structures affect the overtopping of a tailings dam?
	Q.2.5	Dam Type	Whether a tailings dam is constructed in multiple stages (raising) or single stages (such as retention dams) is expected to affect the overtopping of tailings dams. To what extent does the tailings dam construction technique affect the overtopping of a tailings dam?
Slope Instability	Q.3.1	Seismicity	The seismicity of the region where the tailings dam is constructed is expected to have an effect on the slope instability (structural failure) of the tailings dam. To what extent does seismicity affect the slope instability (structural failure) of a tailings dam?
	Q.3.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to affect the slope instability (structural failure) of the dam. To what extent does the construction material affect the slope instability (structural failure) of a tailings dam?

QS	Code	Parameter	Question
	Q.3.3	Seepage control	Seepage control in a tailings dam by means of a pump or liner is expected to have an impact on the slope instability (structural failure) of the dam. To what extent do seepage control practices affect the slope instability (structural failure) of a tailings dam?
	Q.3.4	Drainage facilities	Drainage (removal) of water accumulated in a tailings dam by means of drains or decants is expected to have an effect on the slope instability (structural failure) of the dam. To what extent do drainage practices affect the slope instability (structural failure) of a tailings dam?
	Q.3.5	Phreatic surface	Monitoring and control of the water table (phreatic surface) in deposited tailings in a tailings dam is expected to have an effect on the slope instability (structural failure) of the dam. To what extent does water table monitoring and control affect the slope instability (structural failure) of a tailings dam?
	Q.3.6	Height and inclination	The height and slope gradient of a tailings dam are expected to affect the slope instability (structural failure) of the dam. To what extent do dam height and slope gradient affect the slope instability (structural failure) of a tailings dam?
	Q.3.7	Erosion	The exposure of the tailings dam body to erosion is expected to have an effect on the slope instability (structural failure) of the dam. To what extent does erosion exposure affect the slope instability (structural failure) of a tailings dam?
	Q.3.8	Dam Type	The construction technique of the tailings dam is expected to affect the slope instability of the tailings dam. To what extent does the tailings dam construction technique affect the slope instability of a tailings dam?
Internal Erosion	Q.4.1	Seepage control	Controlling seepage in a tailings dam with a pump or liner, is expected to be effective on internal erosion of the dam body. To what extent do seepage control practices affect internal erosion of a tailings dam body?
	Q.4.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to have an impact on the internal erosion of the dam body. To what extent does the construction material affect the occurrence of internal erosion of a tailings dam body?
	Q.4.3	Phreatic surface	Monitoring and control of the water table (phreatic surface) in deposited tailings in a tailings dam is expected to have an impact on internal erosion of the dam body. To what extent does water table monitoring and control affect the occurrence of internal erosion of a tailings dam body?
	Q.4.4	Dry beach location and width	The location and width of the tailings beach formed by the separating of tailings from water in a tailings dam is expected to have an impact on internal erosion of the dam body. To what extent does the location and width of the tailings beach affect internal erosion of the body of a tailings dam?
	Q.4.5	Dam Type	The construction technique of the tailings dam is expected to have an impact on internal erosion of the tailings dam body. To what extent does the tailings dam construction technique affect the occurrence of internal erosion of a tailings dam body?
Foundation Failure	Q.5.1	Seepage control	Seepage control in a tailings dam, such as pumps or liners, is expected to have an impact on the failure of the dam foundation. To what extent do seepage control practices affect the foundation failure of a tailings dam?
	Q.5.2	Drainage facilities	Drainage (removal) of accumulated water in the tailings dam by means of drains or decants is expected to have an impact on the foundation failure of the dam. To what extent do drainage practices affect the foundation failure of a tailings dam?
	Q.5.3	Foundation properties	The properties of the foundation material on which the tailings dam sits (solid, fractured, soft, etc.) are expected to have an impact on the foundation failure of the dam. To what extent do the properties of the foundation material affect the foundation failure of a tailings dam?
	Q.5.4	Groundwater condition	The groundwater condition of the foundation on which the tailings dam sits is expected to have an impact on the foundation failure of the dam. To what extent does the groundwater condition affect the foundation failure of a tailings dam?
	Q.5.5	Seismicity	The seismicity of the region where the tailings dam is built is expected to have an impact on the foundation failure of the tailings dam. To what extent does the earthquake condition (seismicity) affect the foundation failure of a tailings dam?
	Q.5.6	Subsidence	The susceptibility of the foundation on which the tailings dam sits to subsidence or settlement is expected to have an impact on the failure of the dam due to foundation failure. To what extent does the susceptibility to subsidence affect the foundation failure of a tailings dam?
	Q.5.7	Dam Type	The construction technique of a tailings dam is expected to have an impact on the foundation failure of a tailings dam. To what extent does the tailings dam construction technique affect the foundation failure of a tailings dam?

Table A. 3: Questionnaire on Active Dam Management in the Failure Potential Survey

QS	Code	Parameter	Question
Dam Safety Management	Q.6.1	Dam safety monitoring	Measurement and monitoring of seismicity, water level, body movement, etc. at the tailings dam is expected to be effective in preventing potential dam failure. How effective is monitoring activities in dam safety management?
	Q.6.2	Warning system	The installation of a warning system to ensure the safety of the tailings dam is expected to be effective in preventing the potential failure of the dam. How effective is a warning system in dam safety management?
	Q.6.3	Emergency planning	The presence of an emergency plan for potential hazards at the tailings dam is expected to be effective in preventing the potential failure of the dam. How effective is the emergency plan in dam safety management?
	Q.6.4	Training and safety culture of workers	It is expected that workers or officials working on the tailings dam, recognizing and reporting potential hazards and knowing how to act in possible situations will be effective in preventing the possible failure of the dam. Accordingly; How effective is employee training and safety culture in dam safety management?
	Q.6.5	Supervision and responsibility	Having officials in charge of the tailings dam and having the dam under surveillance are expected to be effective in preventing the possible failure of the dam. How effective is having supervision and responsible officials in dam safety management?
Internal Management	Q.7.1	Design and construction	Construction of a tailings dam according to a specific design (standard) is expected to be effective in preventing the possible failure of the dam. Accordingly; To what extent is the specific design effective in internal management of a tailings dam?
	Q.7.2	Qualification and Experience	The competence and experience of the consultant, contractor or operator involved in the construction and operation of the tailings dam is expected to be effective in preventing potential dam failure. Accordingly, how effective are competence and experience in internal management of a tailings dam?
	Q.7.3	Maintenance practices	The occurrence of an event requiring maintenance to the dam during the construction or operation of the tailings dam is considered to be an indicator of poor dam management. Accordingly, what level of indicator is maintenance practices about internal management of a tailings dam?
External Management	Q.8.1	External Audit	Third party audit or technical review of the construction and operation of the tailings dam is expected to be effective in preventing tailings dam failure. Accordingly, what is the level of effectiveness of the technical review on the external management of the dam?
	Q.8.2	External monitoring	Monitoring of the performance of the tailings dam by the relevant authorities is expected to be effective in preventing the failure of the tailings dam. Accordingly, what is the level of effectiveness of monitoring on the external management of the dam?
	Q.8.3	Regulatory control	Regulatory control of those responsible for the tailings dam by the relevant authorities or administrations is expected to be effective in preventing the failure of the tailings dam. Accordingly, what is the level of effectiveness of regulatory control on the external management of the dam?

Table A. 4: Questionnaire on Active Dam Failure -General Evaluations in the Failure Potential Survey

QS	Code	Parameter	Question
Active Dam Failure - General Evaluations	Q.9.1	Effect of Failure Modes	Rate the components of External Management according to their effectiveness.
	Q.9.2	Importance of Management Factors	Rate the failure modes that determine the Failure Potential according to their effectiveness
	Q.9.3	Effect of Management Factors on Failure Prevention	Rate the components of the management factor according to their effectiveness

Table A. 5: Questionnaire on Closed Dam Failure Modes in the Failure Potential Survey

QS	Code	Parameter	Question
Overtopping	Q.10.1	Extreme hydraulic events	Extreme hydraulic (meteorological) events such as tropical rainfall, heavy snowmelt or hurricanes in the area where the tailings dam is built are expected to have an impact on the overtopping of a closed tailings dam. Accordingly, to what extent does extreme hydraulic events affect the overtopping of a closed tailings dam?
	Q.10.2	Natural hazards	Natural disasters such as landslides, avalanches or strong winds (cyclones) in the area where the tailings dam is built are expected to have an impact on the overtopping of water accumulated in a closed tailings dam. To what extent does natural disasters affect the overtopping of a closed tailings dam?
	Q.10.3	Flood control facilities	The construction of flood control structures, such as diversion channels for flows from the tailings dam's catchment, or weir structures to discharge flood waters from the reservoir, are expected to have an impact on the overtopping of water accumulated in a closed tailings dam. To what extent are flood control or weir structures effective on the overtopping of a closed tailings dam?
Slope Instability	Q.11.1	Seismicity design	The seismicity of the region where the tailings dam is constructed and the design of the tailings dam closure accordingly is expected to have an impact on the slope instability (structural failure) of the tailings dam. To what extent do seismicity conditions and design affect the slope instability (structural failure) of a closed tailings dam?
	Q.11.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to affect the slope instability (structural failure) of the dam. To what extent does the construction material affect the slope instability (structural failure) of a closed tailings dam?
	Q.11.3	Seepage and drainage measures	In a closed tailings dam, seepage and drainage control practices such as liners, drains, etc. are expected to have an impact on the slope instability (structural failure) of the dam. To what extent do seepage and drainage control practices affect the slope instability (structural failure) of a closed tailings dam?
	Q.11.4	Height and inclination	The height and slope inclination of a closed tailings dam are expected to affect the slope instability (structural failure) of the dam. To what extent do dam height and slope inclination affect the slope instability (structural failure) of a tailings dam?
	Q.11.5	Erosion measures	The erosion exposure of a closed tailings dam body is expected to have an impact on the slope instability (structural failure) of the dam. To what extent does erosion exposure affect the slope instability (structural failure) of a tailings dam?
	Q.11.6	Dam Type	The construction technique of the tailings dam is expected to have an impact on the slope instability of the tailings dam. To what extent does the tailings dam construction technique affect the slope instability of a closed tailings dam?
Internal Erosion	Q.12.1	Seepage and drainage measures	Seepage and drainage measures such as lining, drains, etc. taken for a closed tailings dam are expected to have an impact on internal erosion of the dam body. To what extent do seepage and drainage practices affect internal erosion of a closed tailings dam body?
	Q.12.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to have an impact on internal erosion of the dam body. To what extent does the construction material affect the occurrence of internal erosion in the body of a closed tailings dam?
	Q.12.3	Phreatic surface control	It is expected that controlling the water table (phreatic surface) in the tailings in the dam through practices such as impermeability system, dewatering, etc. will have an impact on internal erosion of the dam body. To what extent does water table control affect occurrence of internal erosion in the body of closed dam?
	Q.12.4	Dam Type	The construction technique of the tailings dam is expected to have an impact on internal erosion of the tailings dam body. To what extent does the tailings dam construction technique affect the occurrence of internal erosion of a closed tailings dam body?
Foundation Failure	Q.13.1	Seepage measures	Seepage measures such as liners, drains, etc. in the tailings dam are expected to be effective in the failure of the dam foundation. To what extent does seepage measures affect the foundation failure of a closed tailings dam?
	Q.13.2	Foundation properties	The properties of the foundation material on which the tailings dam sits (solid, fractured, soft, etc.) are expected to have an impact on the foundation failure of the dam. To what extent do the properties of the foundation material affect the foundation failure of a closed tailings dam?
	Q.13.3	Groundwater condition	The groundwater condition of the foundation on which the tailings dam sits is expected to have an impact on the foundation failure of the dam. To what extent does the groundwater condition affect the foundation failure of a closed tailings dam?

QS	Code	Parameter	Question
	Q.13.4	Seismicity measure	It is expected that taking measures for the seismicity of the site where the tailings dam is constructed will have an impact on the foundation failure of the tailings dam. To what extent do seismicity measures affect the foundation failure of a closed tailings dam?
	Q.13.5	Subsidence measure	The susceptibility of the foundation on which the tailings dam sits to subsidence is expected to be effective in the failure of the dam due to foundation failure. To what extent does the susceptibility to subsidence affect the foundation failure of a closed tailings dam?
	Q.13.6	Dam Type	The construction technique of the tailings dam is expected to have an impact on the foundation failure of the tailings dam. To what extent does the tailings dam construction technique affect the foundation failure of a closed tailings dam?

Table A. 6: Questionnaire on Closed Dam Management in the Failure Potential Survey

QS	Code	Parameter	Question
	Q.14.1	Supervision	Third-party audit or technical review of the tailings dam after closure is expected to be effective in preventing tailings dam failure. Accordingly, what is the level of effectiveness of the technical review on the post-closure management of a tailings dam?
	Q.14.2	Monitoring and warning system	Monitoring of tailings dam performance by the relevant authorities is expected to be effective in preventing tailings dam failure. To what extent does monitoring affect the post-closure management of a tailings dam?
	Q.14.3	Regulatory control at closure	Inspection of the organizations or companies responsible for a closed tailings dam by the relevant authorities or administrations is expected to be effective in preventing tailings dam failure. Accordingly, to what extent does regulatory control affect the post-closure management of a tailings dam?
	Q.14.4	Closure planning	The preparation of a closure plan for the tailings dam and closure according to this plan is expected to be effective in preventing the failure of the tailings dam. Accordingly, to what extent does closure planning affect the post-closure management of a tailings dam?
	Q.14.5	Capital investment	The availability of financial instruments or capital investment for tailings dam closure preparations and implementation is expected to be effective in preventing tailings dam failure. Accordingly, to what extent does capital investment affect the post-closure management of a tailings dam?

Table A. 7: Questionnaire on Closed Dam Failure -General Evaluations in the Failure Potential Survey

QS	Code	Parameter	Question
	Q.15.1	Effect of Failure Modes	Rate the failure modes that determine the Closed Dam Failure Potential according to their effectiveness.
	Q.15.2	Effect of Management Factors on Failure Prevention	Post Closure Management is expected to be effective in eliminating or reducing the factors that can cause a tailings dam to fail. Accordingly, to what extent do you think Post Closure Management will be effective in preventing the failure of a closed tailings dam? Describe this proportion in terms of minimum, average and maximum percentage values. 100% means it will eliminate completely and 0% means it will not eliminate at all.

Table A. 8: Questionnaire on Abandoned Dam Failure Modes in the Failure Potential Survey

QS	Code	Parameter	Question
Overtopping	Q.16.1	Extreme hydraulic events	Extreme hydraulic (meteorological) events such as tropical rainfall, heavy snowmelt or hurricanes in the area where the tailings dam is built are expected to have an impact on the overtopping of an abandoned tailings dam. To what extent does extreme hydraulic events affect the overtopping of an abandoned tailings dam?
	Q.16.2	Natural hazards	Natural disasters such as landslides, avalanches or strong winds (cyclones) in the area where the tailings dam is built are expected to be effective on the overtopping of water accumulated in an abandoned tailings dam. To what extent does natural hazards affect the overtopping of an abandoned tailings dam?
	Q.16.3	Flood control facilities	The construction of flood control structures such as diversion channels for flows from the catchment of the tailings dam, or weir structures to discharge floodwaters from the reservoir, is expected to be effective on the overtopping of waters accumulated in an abandoned tailings dam. To what extent does flood control and weir structures affect the overtopping of an abandoned tailings dam?
Slope Instability	Q.17.1	Seismicity design	The seismicity of the region where the tailings dam is constructed and whether the tailings dam is designed accordingly are expected to be effective on the slope instability (structural failure) of the tailings dam. To what extent do earthquake conditions and design affect the slope instability (structural failure) of an abandoned tailings dam?
	Q.17.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to affect the slope instability (structural failure) of the dam. To what extent does the construction material affect the slope instability (structural failure) of an abandoned tailings dam?
	Q.17.3	Seepage and drainage measures	Seepage and drainage controls by lining, drains, etc. in an abandoned tailings dam is expected to affect the slope instability (structural failure) of the dam. To what extent do seepage and drainage control practices affect the slope instability (structural failure) of an abandoned tailings dam?
	Q.17.4	Height and inclination	The height and slope inclination of an abandoned tailings dam are expected to affect the slope instability (structural failure) of the dam. To what extent do dam height and slope inclination affect the slope instability (structural failure) of an abandoned tailings dam?
	Q.17.5	Erosion measures	Whether the body of an abandoned tailings dam is exposed to erosion is expected to affect the slope instability (structural failure) of the dam. To what extent does erosion exposure affect the slope instability (structural failure) of an abandoned tailings dam?
	Q.17.6	Dam Type	The construction technique of the tailings dam is expected to affect the slope instability of the tailings dam. To what extent does construction technique affect the slope instability (structural failure) of an abandoned tailings dam?
Internal Erosion	Q.18.1	Seepage and drainage measures	It is expected that whether or not seepage and drainage measures are taken in an abandoned tailings dam by means of lining, drains, etc. will affect internal erosion of the dam body. To what extent do seepage and drainage practices affect internal erosion of the body of an abandoned tailings dam?
	Q.18.2	Construction material	The material from which the tailings dam is constructed (rock, sand-silt, tailings, rubble) is expected to affect internal erosion of the dam body. To what extent does the construction material affect internal erosion of the body of an abandoned tailings dam?
	Q.18.3	Phreatic surface control	The control of the water table (phreatic surface) in the tailings in the dam by means of impervious systems, dewatering, etc. is expected to affect internal erosion of the dam body. To what extent does water table control affect internal erosion of an abandoned tailings dam body?
	Q.18.4	Dam Type	The construction technique of the tailings dam is expected to affect internal erosion of the tailings dam body. To what extent does the tailings dam construction technique affect the occurrence of internal erosion of an abandoned tailings dam body?
Foundation Failure	Q.19.1	Seepage measures	Seepage measures such as liners, drains, etc. taken in the tailings dam is expected to affect the failure of the dam foundation. To what extent do seepage measures affect the foundation failure of an abandoned tailings dam?
	Q.19.2	Foundation properties	The characteristics of the foundation material on which the tailings dam sits (solid, fractured, soft, etc.) are expected to affect the foundation failure of the dam. To what extent does the foundation material affect the foundation failure of an abandoned tailings dam?
	Q.19.3	Groundwater condition	The groundwater condition of the foundation on which the tailings dam sits is expected to affect the foundation failure of the dam. To what extent does the groundwater condition affect the foundation failure of an abandoned tailings dam?

QS	Code	Parameter	Question
	Q.19.4	Seismicity measure	The seismicity of the region where the tailings dam is built and whether or not earthquake countermeasures have been taken are expected to affect the foundation failure of the tailings dam. To what extent do earthquake measures affect the foundation failure of an abandoned tailings dam?
	Q.19.5	Subsidence measure	Whether the foundation on which the tailings dam sits is prone to subsidence is expected to affect the foundation failure of the dam. To what extent does the susceptibility to subsidence affect the foundation failure of an abandoned tailings dam?
	Q.19.6	Dam Type	The construction technique of the tailings dam is expected to affect the foundation failure of the tailings dam. To what extent does the tailings dam construction technique affect the foundation failure of an abandoned tailings dam?

Table A. 9: Questionnaire on Abandoned Dam Management in the Failure Potential Survey

QS	Code	Parameter	Question
	Q.20.1	Supervision	Monitoring the performance of the tailings dam through measurement by the relevant authorities is expected to be effective in preventing the failure of the tailings dam. Accordingly, to what extent is monitoring effective in the management of an abandoned tailings dam?
	Q.20.2	Monitoring and warning system	Supervision of the institutions responsible for an abandoned tailings dam by the relevant authorities or administrations is expected to be effective in preventing the collapse of the tailings dam. Accordingly, to what extent is regulatory control effective in the management of an abandoned tailings dam?
	Q.20.3	Regulatory control at closure	The fact that an abandoned tailings dam has experienced an event in the past that requires a maintenance or technical inspection is expected to provide information on whether the dam is well managed. Accordingly, to what extent does dam behavior provide information about the management of an abandoned tailings dam?

Table A. 10: Questionnaire on Abandoned Dam Failure -General Evaluations in the Failure Potential Survey

QS	Code	Parameter	Question
	Q.21.1	Effect of Failure Modes	Rate the failure modes that determine the Abandoned Dam Failure Potential according to their effectiveness.
	Q.21.2	Effect of Management Factors on Failure Prevention	Abandoned Dam Management is expected to be effective in eliminating or reducing the factors that may cause the tailings dam to fail. To what extent do you think that Abandoned Dam Management will be effective in preventing tailings dam failure? Describe this rate in terms of minimum, average and maximum percentages. 100% means it will completely eliminate, 0% means it will not eliminate at all.

APPENDIX B

QUESTIONNAIRE OF THE TSF FAILURE CONSEQUENCES SURVEY

Table B. 1: Questionnaire on Background Information in the Failure Consequences Survey

QS	Code	Parameter	Question
Background	Q.1.1	-	Name and Surname
	Q.1.2	-	Age
	Q.1.3	-	Educational Level
	Q.1.4	-	What is your experience in the impact assessment, design, construction, operation, inspection, or related areas of tailings dams?
	Q.1.5	-	In the questions on the following pages, the potential social and economic impacts on a community in the event of a tailings dam failure will be assessed using both qualitative (linguistic) descriptions and quantitative (numerical) values. The meaning of qualitative terms can vary from person to person. Please define the minimum, average (expected), and maximum values on a scale of 1 to 10 for the qualitative descriptors: Very High, High, Medium, Low, Very Low Example: One person may define the term “high” as having a value between 7 (minimum) and 9 (maximum), with an average of around 8, while another may define it as ranging from 6 (minimum) to 9 (maximum), with an average of 7.

Table B. 2: Questionnaire on Human Health in the Failure Consequences Survey

QS	Code	Parameter	Question
Severity	Q.2.1	Toxicity	The chemical nature of the waste flowing in the dam failure event is expected to affect the severity of the event. Whether the wastes contain hazardous or dangerous substances for human health will change the severity of the event. Accordingly, to what extent does the toxicity (hazardousness) of the waste affect the severity of the incident?
	Q.2.2	Damage to infrastructure and facilities	Damage or destruction of the main roads of the settlement and/or buildings such as health centers and hospitals as a result of dam failure is expected to affect the severity of the event. Accordingly, at what level will the damage of infrastructure and facilities affect the severity of the incident?
	Q.2.3	Resilience of residences	The resilience of the residences in the settlement that will be affected by the dam collapse is expected to affect the severity of the event. Accordingly, to what extent does the resilience of the residences affect the severity of the event?
	Q.2.4	Quickness of rescue services	The quickness (speed) of rescue services to reach the site is expected to affect the severity of the dam failure event. It is predicted that early intervention will reduce the number of loss of life and permanent health problems. Accordingly, to what extent does the quickness of rescue services affect the severity of the incident?
	Q.2.5	Vulnerability of the region to natural hazards	The fact that the region exposed to the dam failure event is affected by flood and earthquake disasters is taught to be an indicator in measuring the severity of the dam failure event. The occurrence of the dam failure event together with these disasters is expected to increase the severity of the event. Accordingly, to what extent does vulnerability of the area to natural hazards affect the severity of the event?
Degree of Preparedness	Q.3.1	Emergency planning	It is expected that whether or not the mine owner and/or authorized institutions/organizations have an emergency plan for a dam failure event will affect the degree of preparedness of the community for the event. Accordingly, to what extent does Emergency Planning affect the Degree of Preparedness for a dam failure event?

QS	Code	Parameter	Question
	Q.3.2	First aid opportunities	The availability of facilities such as a health center or hospital in the affected settlement or the availability of first aid kits for individuals is expected to affect preparedness for the event. To what extent do First Aid Opportunities affect the Degree of Preparedness for a dam failure event?
	Q.3.3	Early warning	The presence of an early warning opportunities in the settlement that will be affected by the dam failure event is expected to affect the degree of preparedness of the community for the event. Accordingly, to what extent does the presence of an early warning opportunities affect the Degree of Preparedness for a dam failure event?
	Q.3.4	Training	Training or informing community members about the possibility of dam failure is expected to increase the degree of preparedness for the event. Accordingly, to what extent does training affect the Degree of Preparedness for a dam failure?

Table B. 3: Questionnaire on Social and Economic Life in the Failure Consequences Survey

QS	Code	Parameter	Question
Vulnerability	Q.4.1	Dependency on Mining	Dependency on Mining: It is defined as the ratio of number of workers in a community who work in the mine where a tailings dam failure occurs to total number of workers. The higher the proportion of people working in the mine, the higher the dependency on the mine. Accordingly, to what extent does Dependency on Mining affect the Vulnerability of a community to a dam failure event?
	Q.4.2	Diversity of Economic Activities	A community, if engaging in different types of economic activities, is expected to enabling others to replace economic activities lost or damaged by dam failure. Accordingly, to what extent does the diversity of economic activities affect a community's vulnerability to dam failure?
	Q.4.3	Proportion of Vulnerable Groups	Proportion of Vulnerable Groups: It is defined as the ratio of the number of children and the elderly to the total population in a community. According to this definition, to what extent does the Proportion of Vulnerable Groups affect the Vulnerability of a community to a dam failure event?
	Q.4.4	Existence of Indigenous People	Indigenous People: Refers to communities that have been living in a particular region since time immemorial, have a distinctive culture, language, customs and lifestyle, and have a strong living connection to that region. For example: Indian tribes in America, Aborigines in Australia. To what extent does the Presence of Indigenous Peoples affect a community's vulnerability to dam failure?
Social Disturbance	Q.5.1	Unrest	Unrest is considered as a combination of traumatic stress in a community as a result of dam failure, loss of historical and religious cultural assets and damage to the infrastructure in the settlement. Accordingly, to what extent does Unrest affect Social Disturbance in a community as a result of dam failure?
	Q.5.2	Displacement	Displacement is considered as a combination of evacuation of the area in case of dam failure, migration due to destruction or unusable houses, and inability of settlement to provide health and education services. Accordingly, to what extent does Displacement affect the Social Disturbance that may occur in a community as a result of dam failure?
	Q.5.3	Poverty	Poverty is estimated as a combination of loss of community income sources, loss of labor force and loss of ecosystem services as a result of dam failure. Accordingly, to what extent does Poverty affect Social Disturbance in a community as a result of dam failure?
Economic Support	Q.6.1	Compensation	Compensation refers to payments for damages resulting from a dam failure provided by the mine owner and/or the state. Accordingly, to what extent does compensation affect the recovery of adverse effects as a result of dam failure?
	Q.6.2	Insurance	Insurance refers to the existence of insurance opportunities to provide recovery for damages that may arise as a result of dam failure. Accordingly, to what extent does insurance affect recovery of adverse effects as a result of dam failure?
	Q.6.3	Donation	Donation refers to the recovery of damages caused by dam failure through aid campaigns or donations made by local non-governmental organizations (associations, foundations, etc.) and/or the public. Accordingly, to what extent does donation affect the recovery of adverse effects as a result of dam failure?

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Degree	Institution	Year of Graduation
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PUBLICATIONS

1. **Ataman, N.** (2005), “Utilization of industrial wastes of Turkey as abrasive in surface preparation technologies”, M.Sc. Thesis, METU.
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