Incorporating Uncertainty into Dam Closure Risk Assessments

by

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Abstract

Best practice guidance of dam safety management mandates the application of risk assessment in all stages of the lifecycle of dams: design, construction, operation, closure and post closure. Risk can be defined as a measure of the probability and severity of an adverse effect on the public, environment and property (CDA, 2013). Risk assessment is one of the dam risk management system components that provides an answer to the question, “Is the dam safe enough?”

Site-specific dam information is critical for conducting a risk assessment. This information could be missing, incomplete or outdated, which identifies many sources of uncertainties regarding the availability of information (AI). Uncertainties could also be due to geotechnical assumptions, methods used in site investigation, analysis, and design and will be referred to as quality of available information (QAI). Conducting the risk assessment without considering the level of uncertainty in AI and QAI could be misleading. Limited AI could lead to unconsidered high risks, while a lack of QAI could lead to a false interpretation of risk. Confidence in the risk assessment outcomes is related to both the quality of dam information and its availability. Insufficient information and substandard analyses would increase epistemic uncertainty, which would result in low confidence in the estimated risk.

Tailings dams have some added characteristics that may contribute to more AI and QAI challenges than water dams. These challenges are amplified when conducting a long-term risk assessment of facilities. The characteristics include material sources, geochemistry, multi staging in construction, impounding a mix of saturated tailings solids and water (instead of only water) and overlapping the design-construction-operation sequence. Tailings dam properties are site-specific and this contributes to limiting the amount of information that can be shared among sites. Further, there are competing interests with safety goals such as profitability of an operation, which can lead to low levels of AI and QAI if the organization does not have a robust safety management culture.

For long-term risk assessments of tailings dams, not only the current properties of a particular element are needed, but also it is important to include the potential future changes of these properties. While the behaviour of tailings dams components is well documented against known failure modes throughout the active stage, much less is understood about the aging processes that tailings ponds and their dams undergo and how a dam will evolve over time. This challenge increases the complexity of conducting a long-term risk assessment. Additionally, given that risk assessments are required for the long term (i.e., in excess of 100 years), the ownership of a facility may be transferred before the risk-assessment period has expired. It is critically important to have an effective data management plan and to communicate information through changes of personnel and ownership. In order to forecast the long-term behaviour of these facilities, we must have reliable site-specific information about a dam, where reliable information is defined as information that is subject to quality assurance and on ongoing review to ensure its validity and accuracy.

This research evaluates the effects of AI and QAI uncertainties on the potential success of long-term risk assessment of tailings dams. A framework to incorporate the uncertainty into the risk assessments was developed using the most recent state-of-practice risk-analysis tool. The sources of AI and QAI uncertainties affecting the confidence in the estimated risks in tailings dams were identified through the framework based on the industry experience gathered through site visits to western Canadian tailings dams sites.

With many of Alberta's coal mine tailings dams scheduled to close by 2030, a case study from the coal mining industry in Alberta was selected to test the uncertainty evaluation framework. The findings of the case study application are based on our assumptions and hypothetical scenario using site data as a guide and do not reflect the actual risks at the site. The selected failure modes were assessed following closure activities when the closed facility may be at its greatest risk of failure prior to reaching equilibrium. The discussed failure modes have high uncertainty based on the available information and the assumptions. Incorporating these uncertainties through the closure risk assessment poses a low confidence level in the risk estimation.

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I came to Canada with the dream of pursuing my studies in dams, and today, I was able to make that dream a reality because of the support of my supervisor, Dr. Nicholas Beier, and my co-supervisor, Dr. Renato Macciotta.

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1. Introduction

Mining sites require containment structures to store water and waste generated from their operations.The extraction operations in mining require water, which is stored behind the water dams. Many mining operations produce liquid or “slurry” waste known as tailings, which consist of different ratios of fine particles, sand and water. Tailings are stored behind tailings dams. After a mine is closed, tailings dams are subject to the natural forces after the dam transitions into a landform and will stay on the landscape for longer, usually for more than 100 years, while water dams will be removed after the end of the operation (Schafer et al., 2020). This requires the long-term behaviour of this landform to be identified and assessed.

Dam systems and their components deteriorate and evolve over time and require increased maintenance to preserve their performance and manage risks that were not originally anticipated in original designs for operational and loading conditions. (DeNeale et al., 2019). Risk is defined as a measure of the probability and severity of an adverse effect on the public, environment and property (CDA, 2013).

To ensure continued safe operations and achieve successful closure of tailings dams, a risk-informed decision-making process (RIDM) is required, such that potential risks are considered in all stages of the lifecycle of dams: design, construction, operation, monitoring a dam and reservoir and, eventually, successful closure. The dam safety risk assessment informs the RIDM process.

After the 1976 Teton Dam failure, the federal legislation identified a need to develop dam safety risk assessment procedures. The USACE began implementing risk assessment procedures following the 2005 Hurricane Katrina levee failures. (DeNeale et al., 2019).

The risk assessment process is the process by which we can answer the question, “Is the dam safe enough?” through the prediction of the potential behaviour of the dams and associated risks. Then RIDM can be applied to the methods by which risk can be eliminated or controlled. Chapter 2 presents an overview of the risk assessment process and the applied methods.

Morgenstern (2018) summarized after France and Williams (2017), how risk assessment has strengthened the dam safety community in many ways by:

- Recognizing in a formal manner the ways that a dam can fail and the consequences of these failures.
- Focusing monitoring procedures and remediation efforts on the highest risk dams and potential failure modes.
- Using risk assessments as a tool for prioritizing risk reduction actions.

Risk prediction is not simple and the outcomes involve sometimes significant uncertainties. FEMA 2015 identified the uncertainty in the dam safety risk assessment as a result of imperfect knowledge about the present or future state of a dam system.

One of the uncertainty sources associated with the risk assessment outcomes is the availability and quality of available dam information. Dam information is critical for conducting a risk assessment. This includes site data, design details, construction materials, construction method, past behaviour of the structure, historical climate data, etc. The more reliable information we have, the more effective the evaluation of the risk associated with a dam. Such facilities can be designed and managed to account for these risks and be safe and secure such that the risks will not become a burden on the public or the environment. Reliable information is defined as information that is subject to quality assurance and on ongoing review to ensure its validity and accuracy.

Site-specific dam information could be missing, lacking, incomplete or outdated, which identifies many sources of uncertainties regarding the availability of information (AI). The uncertainties could also be due to geotechnical assumptions and methods used in site investigation and analysis. Such uncertainties will be referred to as quality of available information (QAI). Conducting a risk assessment without considering how much of the uncertainty is related to AI and QAI could be misleading. Lack of AI could lead to unconsidered high risks, while lack of QAI could lead to a false estimated risk. Confidence in the risk assessment outcomes is related to both the availability and quality of dam information

The RIDM of closure design of tailings dams incorporates more AI and QAI challenges. Tailings dam properties are site-specific, which limits the amount of information that can be shared among sites. The long-term risk assessment requires not only the current properties of a particular element, but also the potential future change of these properties. An example of this is the potential weathering and degradation of materials and changes in permeability over time. While the behaviour of tailings dams' components is well documented against known failure modes throughout the active stage, much less is understood about the aging processes that tailings ponds and their dams undergo and how the dam will evolve over time.Additionally, given that risk assessments are required for the long term (i.e., in excess of 100 years), the ownership of a facility may be transferred before the risk-assessment period has expired.. It is critical to have an effective data management plan and to communicate information when personnel and ownership change. The availability of reliable site-specific information about a dam is critical to our ability to forecast the long-term behaviour of these facilities. The sources of AI and QAI uncertainty and how to incorporate them in the long-term risk assessment of tailings dams become paramount for RIDM.

The risk assessment process has made good progress in its ability to characterize, analyze and manage risks posed by dams, and the RIDM is now widely considered to be a key component of dam safety in many organizations and industries. However, the current challenge is to expand risk assessment methods to include the uncertainties posed by limited knowledge about information and models. Uncertainties posed by such limited knowledge are less well understood in practice; the methods for dealing with them are still developing, and expertise has yet to be widespread. (Baecher, 2016) .

1.1. Problem Statement

As stated on the previous page, tailingsInformation about tailings dams is critical for conducting a risk assessment. The more reliable information we have, the more effective the evaluation of risks associated with a dam. Confidence in the risk assessment outcomes is related to both AI and QAI. Tailings dams have some added characteristics that may contribute to more AI and QAI challenges than water dams. These challenges are more evident when conducting a long-term risk assessment of these facilities. It is important to examine the level of confidence in the outcomes of long-term risk assessment of tailings dams in the presence of AI and QAI uncertainties needs to be reviewed. Such facilities can adopt RIDM processes for closure plans, designed to account for these risks, and provide for safe and secure structures that will not become a burden on the public or the environment.

1.2. Objectives

The main objectives of the research can be summarized as follows:

1. Identify the sources of AI and QAI uncertainties affecting confidence in the long-term estimated risk of tailings dams.
2. Develop a framework for incorporating uncertainty into a risk assessment process for the closure of tailings dams. The framework should guide dam operators/regulators through the process of risk assessment, showing them how to identify and assess the effects of AI and QAI uncertainties on the potential success of risk estimation.
3. Evaluate the uncertainty framework through a detailed long-term risk assessment case study of a coal mine tailing dam closure plan.

1.3. Methodology

The proposed methodology consists of developing the research objectives through:

Objective 1: To identify the source of AI and QAI uncertainties based on the key results of the interviews that Schafer et al. (2019) and Schafer et al. (2020) conducted with individuals who have experience with tailings dams and closure in Alberta. The skilled practitioners included world-renowned experts, consultants and mine operators. A site visit was made to western Canadian tailings dams during this research and the industry experience gathered was used when discussing AI and QAI sources, in addition to relevant tailings dams literature and guidelines.

Objective 2: To use the work published by Silva et al. (2008) as a foundation for the development of the uncertainty framework. Silva et al. (2008) presented an approach to assess confidence in geotechnical engineering along the life-cycle phases of conventional earth structures. The approach by Silva et al. (2008) was customized for tailings dams. The current best practice tailings dams' approach presented by Morgenstern (2018) and Oboni (2020) was used as a baseline to customize Silva's approach for tailings dams. It was also used to consider the sources of uncertainties in terms of AI and QAI discussed in Objective 1. The developed uncertainty framework was integrated to a novel risk assessment tool for assessing risks associated with closure plans for tailings dams. The generalized failure modes and effects analysis (G-FMEA) developed by Schafer et al. (2021) was adopted in this research.

Objective 3: To present the detailed coal mine site-specific risk assessment case study. The purpose of this site-specific application was to present a scenario on how to implement the LOC framework through the risk assessment process. The case study example is based on a real case study layout and components. Assumptions and hypothetical scenarios are used to better show the uncertainty ranking and do not reflect the actual risks at the site. The uncertainties that could affect the confidence of closure risk assessment are discussed in detail for two failure modes.

1.4. Outline of the Thesis

This thesis is organized into five chapters. Chapter 1 provides a brief introduction, problem statements, objective, methodology and outlines of the thesis.

Chapter 2 is a literature review of the risk assessment process and its components, including uncertainty in estimated risk and its sources, and the sources of AI and QAI uncertainties associated with conducting a long-term risk assessment of tailings dam. Chapter 3 presents the development of the LOC framework to incorporate uncertainty in risk estimating. The main focus of the coal mine case study application is presented in Chapter 4. A summary of this research, its findings, conclusions and future work are presented in Chapter 5.

2. Dam Safety Risk Assessment

2.1. Guiding Principles and Terminology

The purpose of this section is to provide an overview of dam safety risk assessment as a central component of dam safety risk management. The dam safety risk management process has the same fundamental components of the traditional dam safety management process –surveillance, periodic dam safety reviews, and operation and maintenance procedures. However, the risk-based process enhances traditional dam safety management through an integrated process that permits risk-informed decision-making (RIDM), so the risks posed by dams are considered (Hartford and Baecher, 2004).

The International Commission on Large Dams (ICOLD) (2005) identifies risk management as the systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring risk.

In most relevant literature, the dam safety risk management process consists of two main components: risk assessment and risk control. Risk assessment is the process by which we can answer the question, "Is the dam safe enough?" by predicting and assessing the potential behaviour of a dam and the associated risks. Then, risk-informed decisions can be made regarding the methods by which risk can be eliminated, reduced and/or controlled. ICOLD (2005) identifies risk assessment as the process that aids in making a decision on whether existing risks are acceptable and the present risk measures are adequate or whether alternative risk reduction measures are needed. (ICOLD 2005). Best practice dam safety guidelines refer to the risk assessment process as a fundamental tenet of dam safety (CDA 2013, MAC 2017)

Risk assessment incorporates risk analysis and risk evaluation. Risk analysis is the use of available information to estimate the risk to health, property or the environment from hazards (ICOLD 2005). It is a structured process aimed at identifying the likelihood of failure of the dam or dam components and the extent of the consequences of failure. It generates information about the potential risk in the system and the contributors to this risk (Hartford and Baecher, 2004). The risk analysis component is the focus of this research.

After the risk analysis, the risk assessment process adds the risk evaluation step. Risk evaluation is a process of judging the significance of the estimated risk and clearly states the values and philosophies of the owner and regulatory authorities (Hartford and Baecher, 2004). Risk estimated in this risk analysis step is evaluated against adopted criteria outlined by the owner, regulator, stakeholders and public.

Hartford and Beaker 2004 highlight the importance of considering risk communication as a separate main component of risk management. Risk communication is a consistent framework for communication and interactive-exchange of risk analysis and risk evaluation information among stakeholders of dam projects (Hartford and Beaker, 2004). The 2013 edition of the Canadian dam association's Dam Safety Guidelines (CDA,2013) considers this component through the supporting processes of the dam safety management system. The risk communication component has recently been identified as a big challenge for the effective implementation of risk-informed decisions in tailings dam facilities (Macciotta and Lefsrud, 2020).

The risk analysis process generally involves the following activities adapted from Hartford and Baecher (2004):

1. Scope definition and selection of analysis methods
2. Hazard identification or failure-causing conditions
3. Failure mode identification
4. Estimation of the likelihood of dam failure (probability)
5. Estimation of consequences corresponding to each failure event
6. Risk estimation
7. Uncertainty and sensitivity analysis
8. Documentation
9. Expert independent review and/or verification (if possible)
10. Analysis update (if required)

Scope definition or defining the system

This includes familiarization with the dam and all sub-systems that make up the dam system. Figure 2-1 shows a schematic example of dam system components (Hartford and Baecher, 2004).

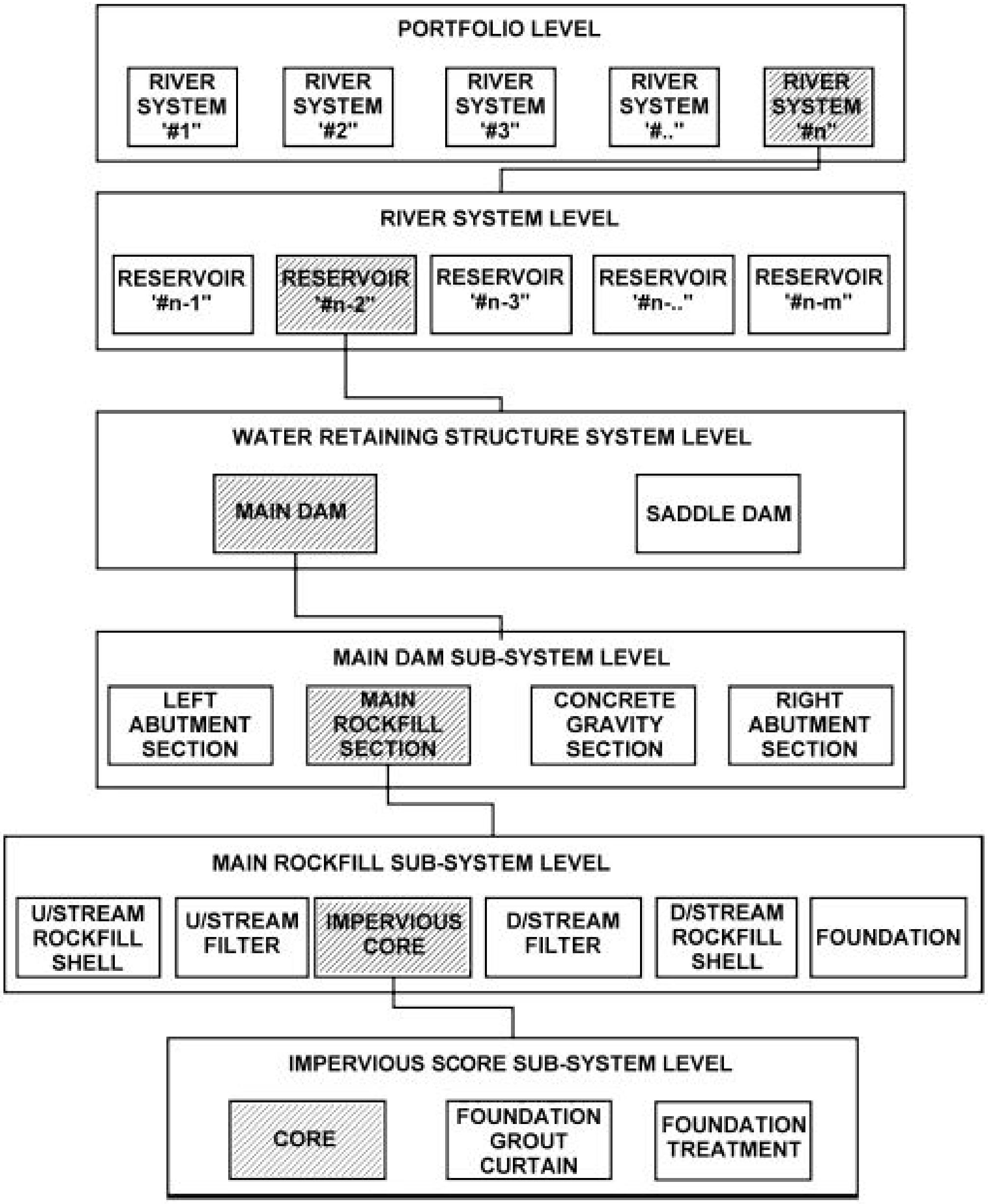


Figure 2-1:Example of dam system components (Hartford and Baecher, 2004)

Hazard identification

The hazard or loading condition is the threat which may generate risk in the dam system. It is the source of harm or a situation with the potential to cause loss. Hazard may result from an external cause (e.g., earthquake, flood, or human agency) or an internal weakness in the system, with the potential to initiate a mechanism of a certain failure mode (ICOLD 2005).

Failure mode identification

The way that the failure of a dam can happen includes all sequences of events from initiation to failure for a given loading condition (DeNeale et al., 2019, FEMA 2015). (FEMA 2015). The terminology of failure used in this study follows the definition presented by Schafer et al (2021). This includes either the ultimate failure of a dam—collapse leading to catastrophic failure (adopted from the Global Tailings Standard (Global Tailings Review, 2020)—or serviceability failure, failure to perform as intended.

Estimation of the likelihood of dam failure (probability)

The likelihood is the chance or degree of belief that a specific outcome or consequence will occur. Probability is a quantitative measurement of the likelihood (DeNeale et al., 2019, USACE 2014a).

Estimation of consequences

The consequence is the impact in the downstream and other areas resulting from the failure of the dam or its appurtenances (ICOLD 2005). Only negative impacts are usually considered

Risk estimation

Risk can be defined as a measure of the probability and severity of an adverse effect on the public, environment and property (CDA, 2013). The risk estimation shapes the main output of risk analysis and can be achieved using the overall estimates of hazard, the likelihood of failure and consequence.

The estimated risk will provide descriptions of the risk in one, some or all of the following categories:

- Individual risk to the public
- Societal risk to the public
- Occupational risk to workers
- Environmental risk
- Commercial risk to the owner
- Social and economic risk

The estimation strategy for probabilities of hazards, the likelihood of dam failure and consequences can be either qualitative, quantitative or both. However, the probabilities theory used to qualitate or quantify the likelihood and consequences of different risks may have some limitations in the representation and treatment of uncertainty posed by poor knowledge (Baraldi et al. 2014), such as uncertainty in the future behaviour of tailings dams. This limation is beyond the scope of this work.

Uncertainty

> This is "the result of imperfect knowledge about the present or future state of a system, event, situation, or population under consideration" (FEMA 2015). The analysis of uncertainties associated with dam information, risk analysis methods, and models used to estimate the associated risks posed by dams is important (Hartford and Baecher, 2004). The focus of this research is the uncertainty associated with dam information such as limited available historical climate records of the dam site.

Sensitivity analysis

> This is a process which provides an indication of how widespread the results can be if a certain parameter is varied within realistic bounds (Hartford and Baecher, 2004).

Expert independent review and/or verification (when possible)

> The independent review provides an "independent evaluation of all aspects of the planning, design, construction, operation, maintenance of a tailings facility by competent, objective, third-party review on behalf of the Owner" MAC (2017). A formal review of risk analysis outcomes at appropriate times, by someone other than the analyst is important. the analysis must be rational in order for someone to confirm that it is correct and has integrity(Hartford and Baecher, 2004).

Analysis update

> The analysis should be performed throughout the life of the dam and as new information becomes available (Hartford and Baecher, 2004).

The risk analysis activities can be conducted through various frameworks based on the methods used. These methods include:

1. Failure modes and effects analysis (FMEA) and associated methods such as potential failure modes analysis (PFMA) and Alberta Environment and Parks' PFMA (AEP's PFMA) (Hartford and Baecher, 2004)
2. Event tree analysis (ETA)
3. Fault tree analysis (FTA).

The focus of this research is the risk assessment component, in particular, activity number seven (uncertainty and sensitivity analysis). The dam safety risk management components and their definitions are summarized in Figure 2-2 after Hartford and Baecher, 2004. The fundamental questions which risk assessment can answer, associated with the general activities in the process, are summarized after the mining association of Canada (MAC ,2017) and Hartford and Baecher (2004) in Figure 2-3

1 Risk Analysis

Using available information to estimate the risk to health, property or the environment, caused by unwanted events (hazard).

2 Risk Evaluation

Understanding and judging the significance of risk based on values and philosophies of the owner and regulatory authorities.

3 Risk Communication

Consistent framework for communication and interactive-exchange of risk analysis and risk evaluation information among stakeholders of dam project. *

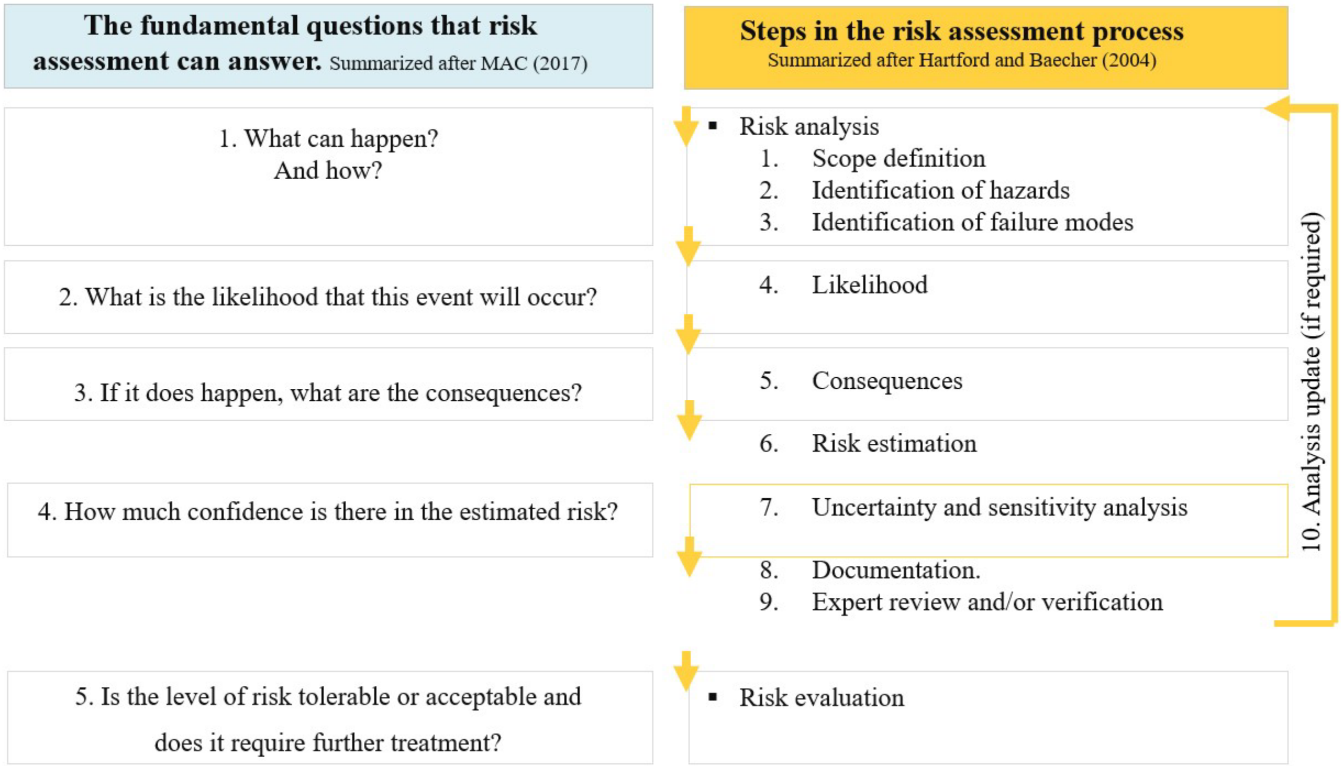
4 Risk Control

- Operation and maintenance procedures
- Risk reduction measures
- Emergency plans

The outcomes of the risk analysis and risk evaluation processes are integrated and decisions are made regarding the risk control process, taking into consideration the consistent framework of risk communication.

*Stakeholders of the dam project include owners, designers, surveillance engineers, dam safety review engineers, operations and maintenance staff, emergency planners, decision-makers and regulators. Dam project stakeholders have varying degrees of connections to the dam, along with different backgrounds and experience. Some have a more sophisticated level of understanding about how the dam works, and the risks that the dam poses.

Figure 2-2:The dam safety risk management components summarized after Hartford and Baecher (2004)



The fundamental questions that risk assessment can answer. Summarized after MAC (2017)	**Steps in the risk assessment process** Summarized after Hartford and Baecher (2004)
1. What can happen? And how?	▪ Risk analysis 1. Scope definition 2. Identification of hazards 3. Identification of failure modes
2. What is the likelihood that this event will occur?	4. Likelihood
3. If it does happen, what are the consequences?	5. Consequences 6. Risk estimation
4. How much confidence is there in the estimated risk?	7. Uncertainty and sensitivity analysis 8. Documentation. 9. Expert review and/or verification
5. Is the level of risk tolerable or acceptable and does it require further treatment?	▪ Risk evaluation

Figure 2-3: The fundamental questions that risk assessment can answer associated with the steps in the risk assessment, summarized after MAC (2017) and Hartford and Baecher (2004).

FMEA is a method of risk analysis by which the consequences of individual component failure modes are systematically identified and analyzed. It determines what can happen if a specific element of the system fails and how this failure of an element can lead to overall system failure (Hartford and Baecher, 2004). This tool determines the risk level for all potential failure modes based on a two-dimensional risk rating (likelihood – consequence).

Conducting FMEA involves the following structure (Hartford and Baecher, 2004):

1. Define the system.

2. Separate the system into its functional sub-systems.

3. Systematically separate the sub-systems into key elements and elemental functions.

4. Analyze failure modes for each element.

5. Assess direct failure effects and operational consequences for each failure mode of the element.

6. Summarize findings.

7. Repeat and update the analysis as necessary.

The main limitation of applying FMEA is that it is incapable of including information about the dam's evolution over time and the degradation of the dam components. The inability to incorporate the time element has critical effects on conducting a long-term risk assessment for tailings dams, which evolve significantly over time. In this way, tailings dams differ from other dams such as water dams, which tend not to change. Further, identifying and assessing all potential failure modes for each dam element require considering significant volumes of information (Dos Santos et al , 2012). This means that site-specific dam information has the potential to increase uncertainties regarding availability of information (AI) and quality of available information (QAI) . Another important limitation is that it is challenging to consider cascading effects and combined effects from the failure of different components.

Schafer et al. (2021) developed a modified FMEA that incorporates the element of time (i.e., how the dam evolves) to be considered for the evolution of the system and is referred to as the generalized FMEA. The G-FMEA presents the outcomes of the risk estimated through a three-dimensional risk rating (likelihood – consequence - time) and will be discussed in detail in Chapter 3.

2.2. Uncertainty in Estimated Risk

Risk prediction is not simple and the outcome involves its own, sometimes large, uncertainties. Uncertainty is a result of imperfect knowledge about the present or future state of a dam system. (FEMA 2015). The implementation of risk analysis may be challenging because of gaps in knowledge, uncertainty associated with the mechanism of dam failure, and difficulty in communicating results with stakeholders. Uncertainty will continue to be a key aspect of the dam safety risk assessment process (DeNeale et al., 2019).

FEMA (2015) identifies the risk informed decision making (RIDM) as a decision made not only based on the risk estimated through risk analysis but also by considering confidence in risk estimates and risk uncertainty.

Hartford and Baecher (2004) considered the formal treatment of the uncertainties that are ever present in dam safety practice as a separate main step of risk analysis activities. This includes the identification of uncertainty in the analysis and the degree of confidence in the result.

The estimated risk should be accompanied by “a statement of the degree of confidence in the estimate.” The statement of the degree of confidence describes the extent to which the result of the risk analysis can be reliable during the decision-making process (Hartford and Baecher, 2004). In this research, the statement of the degree of confidence will be referred to as the “level of confidence.” However, Hartford and Baecher (2004) did not present a comprehensive plan for expressing confidence and evaluating the uncertainty.

Assessing the likelihood and consequence rating in tailings dams may involve uncertainties caused by various factors such as a lack of data, lack of system understanding, uncertain future operating conditions or uncertain maintenance, and regional development at the site post closure. Further, these uncertainties may increase in the medium-to-long-term as there is limited information regarding how a tailings dam ages over time. This knowledge gap poses uncertainties and issues (Schafer et al., 2021; Robertson et al., 2006).

Uncertainty in dam safety is usually classified into aleatoric uncertainty (associated with natural variability) or epistemic uncertainty (uncertainty associated with knowledge limitations) (DeNeale et al., 2019).

Aleatory uncertainty (uncertainty in the world) is the uncertainty with respect to the natural variability of the world regardless of people’s opinions, knowledge, or beliefs. (e.g., when and where will an earthquake occur?). Another name for aleatory uncertainty is “known knowns.”

Epistemic uncertainty (uncertainty in the mind) is the uncertainty posed by insufficient or limited knowledge with which to confidently predict an outcome (Baecher, 2016). The confidence in estimating a certain risk is not high because we lack the knowledge and/or ability to understand and assess current or future potential risks. Another name of epistemic uncertainty is “known unknowns.” However, Probabilistic approaches can not capture well, at the moment, epistemic uncertainty in future behaviour of tailings dams and this is beyond the scope of this work.

Epistemic uncertainty has three main sources: parameters, models (Baecher, 2016, Drouin et al., 2009) and completeness (Drouin et al., 2009).

Parameters uncertainty is defined as the inability to assess exactly the parametric values which are required in the risk analysis (Baecher, 2016). The parametric values are imprecisely known due to lack of available information and /or not reliable available information.

Example: There is a gap in our ability to confidently estimate the current risk for dam body failure modes if information such as the construction method is not available. Further, in assessing the long-term risk which may be triggered by climate change, the available historical base of information is critical. If the prediction period is larger than the available historical climate information, assessing the risk becomes a guessing game and involves significant uncertainty. Long term risk assessments of failure modes triggered by climate change after the year 2100 have a high degree of uncertainty (Schafer 2022).

Model uncertainty is defined as the inability of a model, design technique, analyst or analysis tool to represent a system's behaviour precisely or to represent a model that could be changing over time in little-known ways (Baecher 2016).

Example: In methods such as failure modes and effects analysis, the risk is divided into failure modes. Each failure mode is assessed separately, by considering a certain trigger. It is acknowledged that the failures of a dam are often posed by a complex series of adverse conditions rather than a simple design or construction error, or single trigger (Hartford and Baecher, 2004). The limitations of the FMEA application, such as ignoring the multiple and simultaneous failures and the time dependence risk analysis, are examples of analysis tool uncertainty. In events such as the aging process of tailings dams, the triggers could change in ways that are not known to the analyst.

Drouin et al. (2009) mentioned a third type of epistemic uncertainty: completeness uncertainty. This relates to risks that are not considered in the analysis, either known or unknown risks. Incompleteness known uncertainty includes risks which are not considered due to the scope of the risk analysis (e.g., geotechnical, environmental, social) or the level of the risk analysis process. Some failure modes or effects may have been omitted as these are not within the scope of the analysis, or their relative contributions are believed to be negligible. Further, "We ignore the risks that are hardest to measure, even when they pose the greatest threats to our well-being" (Silver, N, 2015). Incompleteness unknowns uncertainty includes risk analysis that may have omitted some failure modes because some failure modes are simply unknown (Doruin et al., 2009). We simply don't know them. These are labeled "unknowns unknowns." Baecher (2016) refers to this as the deeper uncertainties in risk analysis, a major challenge for future infrastructure safety. The challenges become planning and designing strategies for grappling with this kind of uncertainty. The incompleteness uncertainty poses new unknown risks which were not originally anticipated in the risk assessment design phase. (We don’t know what the issues are that we don’t know). The aging process of tailings dams could be considered as a deeper model uncertainty.

The risk assessment methods have advanced in their ability to characterize, analyze and manage aleatory uncertainty, while epistemic uncertainties are less well understood in practice, and the methods for identifying and assessing them are still emerging (Baecher, 2016).

This research presents a descriptive translation of parameter epistemic uncertainty into confidence in the outputs of the risk analysis and will be referred to as the level of confidence framework (LOC). The LOC framework uses different descriptive data categories which have different levels of uncertainties that affect the confidence in the estimated risk in a comprehensive but simple manner that can be readily applied by the practitioner.

Parameter uncertainties have two main sources: the limited available information and not reliable available information. The parameters required for assessing specific failure modes could be missing, lacking, incomplete or outdated, which identifies many sources of uncertainties regarding AI. The parameter uncertainties could also be due to geotechnical engineering, methods used in site investigation and lab test assumptions, and methods followed when analyzing the obtained information. What will be referred to as QAI.

AI is more related to the dam safety management program rather than the geotechnical aspects. An example of this is a level of documentation in the design memorandum, construction as-built record, and inspection reports.

Geotechnical engineering poses two levels of QAI uncertainty that affect the confidence in the values of parameters. The first is related to the level of field investigation and lab testing conducted. This includes the methods and techniques used (how suitable the techniques are in cases of SPT, CPT, and measurement errors, for example). Further, time and space limitations through site investigation pose poor representativeness of sampling schemes (Baecher, 2016). Even with a high level of field investigation and the use of suitable techniques, we cannot properly identify the real material parameters in the field about how the soil state varies from point to point throughout a geological stratum and how one soil type blends into another (Jefferies and Been, 2016).

The second level of uncertainty in geotechnical engineering involves data handling, simplifications in the model and the calculations series to obtain the parameters (Baecher, 2016). Another source of uncertainty is the implementation of empirical equations, using the normal distribution and mean to represent a range of the values obtained (Duncan, 2000).

Conducting the risk assessment without considering how much of the uncertainty is in AI and QAI could be misleading. A lack of AI could lead to unconsidered high risks, while a lack of QAI could lead to a misleading estimate of risk. Confidence in the risk assessment outcomes is related to both the availability and quality of available dam information (AI, QAI).

Tailings dams have some added characteristics that may contribute to more AI and QAI challenges than water dams. These added characteristics are discussed in detail in Section 2.3.

2.3.Uncertainty in Risk Assessment of Tailings Dams

Both water and tailings dams should have risk-informed design, operation, monitoring and (if required) a risk-informed closure plan to clarify the risks associated with these structures, such that these risks are appropriately monitored and managed. The dam safety risk assessment can inform this process.

The structure for conducting a risk assessment is the same for water dams and tailings dams. However, tailings dams have some added characteristics that may contribute to more AI and QAI challenges. The added characteristics are discussed in detail in this section and summarized in Figure 2-5. The challenges are amplified when conducting a long-term risk assessment of these facilities. It is critical to have a thorough understanding of sources of AI and QAI uncertainties and associated effects on the confidence in estimated risk. This can provide dam owners, operators, engineers, regulators, and stakeholders with the initial necessary information as to when efforts should be spent to decrease the uncertainties and upgrade the confidence in risk analysis outcomes. This aids in more meaningful RIDM to ensure public safety and prioritize mitigation solutions.

The sources of AI and QAI uncertainties in the risk assessment of tailings dams are highlighted in this section based on interviews conducted by Schafer et al. (2019) and Schafer et al. (2020) with individuals who have experience with tailings dams and dam closures in Alberta. The skilled practitioners included world-renowned experts, consultants and mine operators. A site visit to western Canadian tailings dams was conducted during this research and the industry experience gathered was used in AI and QAI discussions. Relevant tailings dams literature was also used in the research. The AI and QAI sources affecting the confidence in the long-term risk assessment of tailing dams are discussed in the context of the following main points:

1. More risks are associated with tailings dams than with water dams.

Water dams and tailings dams share the basic principles of earth dam engineering. However, tailings dams have added characteristics in terms of material sources, geochemistry, multi-staging in construction, and impounding a mix of saturated tailings solids and water, as opposed to only water and overlapping design-construction-operation sequences. Those characteristics may contribute to more associated risks leading to a higher failure percentage in tailings dams than in water dams (McLeod et al. 2015; Mittal and Morgenstern, 1975). The material sources, multi-staging in construction and saturated mix of tailings and water pose higher physical risks, while the nature of tailings poses geochemistry risks. Tailings dams' risk assessment should take into account the physical and chemical risks of the tailings facility (MAC, 2017). Conducting a tailings dam risk assessment requires more information than that used in water dams, as more risks are associated with tailings dams. For example, while water dams require only unit weight and height of water confined behind the dam, the properties of the mix of tailings and water behind the dam structure are more complex and subject to change. Both chemical and physical properties for tailings are required. For instance, physical and chemical properties for a coal tailings sample may include specific gravity, sand-sized particles, silt-sized particles, clay-sized particles, liquid limit, plastic limit, plasticity index, pH and electrical conductivity. (Islam et al., 2020). The more information required to assess the risks, the more AI and QAI sources are involved.

2. Tailings dams evolve over time and the system components are subject to physical and chemical changes.

There are many features of tailings dams that may evolve over time such as clogging of drains, aging of sands, aging of pipes (Schafer et al., 2019), as shown in Figure 2-4. Considering the design conditions of these features in risk assessment and ignoring the aging of a dam over time is a source of uncertainty.

It is essential to the risk management process to have a good understanding of the behaviour of the tailing material to correctly model the key aspects to forecast potential changes (Berghe et al., 2011).

Tailings properties are one key components of tailings dams which are subject to physical and chemical changes over time. The physical changes of tailings vary depending on how the tailings are deposited and stored (e.g., sedimentation, consolidation, desiccation, freeze thaw). Understanding the consolidation and strength behaviour of tailings is essential to assess risks such as erosion and the instability of dam structures containing tailings (Islam et al., 2020). The chemical changes are often a function of exposure to atmospheric oxidation (reactions with air and natural water) (Kossoff et al., 2014) or due to reactions with the foundation soil (Berghe et al., 2011, Ballard et al, 2008). The chemical changes in tailings lead to unexpected behaviour of dams. For example, undesired chemical reactions may reduce the efficiency of the drainage system (Berghe et al., 2011, Ballard et al, 2008). Conducting a long-term risk assessment of the tailings dam requires not only the current properties but also the potential change to these properties. Less is understood about the aging processes that tailings ponds and their dams undergo in perpetuity and how the dam will evolve over time (Schafer et al.,2021, Robertson et al., 2006). There is a lack of available published information about the long-term behavior of tailings dams (Schafer et al., 2020). This challenge increases the complexity of conducting a long-term risk assessment. The physical and chemical changes to tailings properties require conducting continuous investigations and sample tests to confirm material properties and behaviour. Using the design parameters of tailings dam components to assess the risks at the closure phase is an example of QAI uncertainty. Internal erosion and static liquefaction failure modes have a higher degree of uncertainty regarding their development in the long term compared to other failure modes (Schafer at al., 2020).

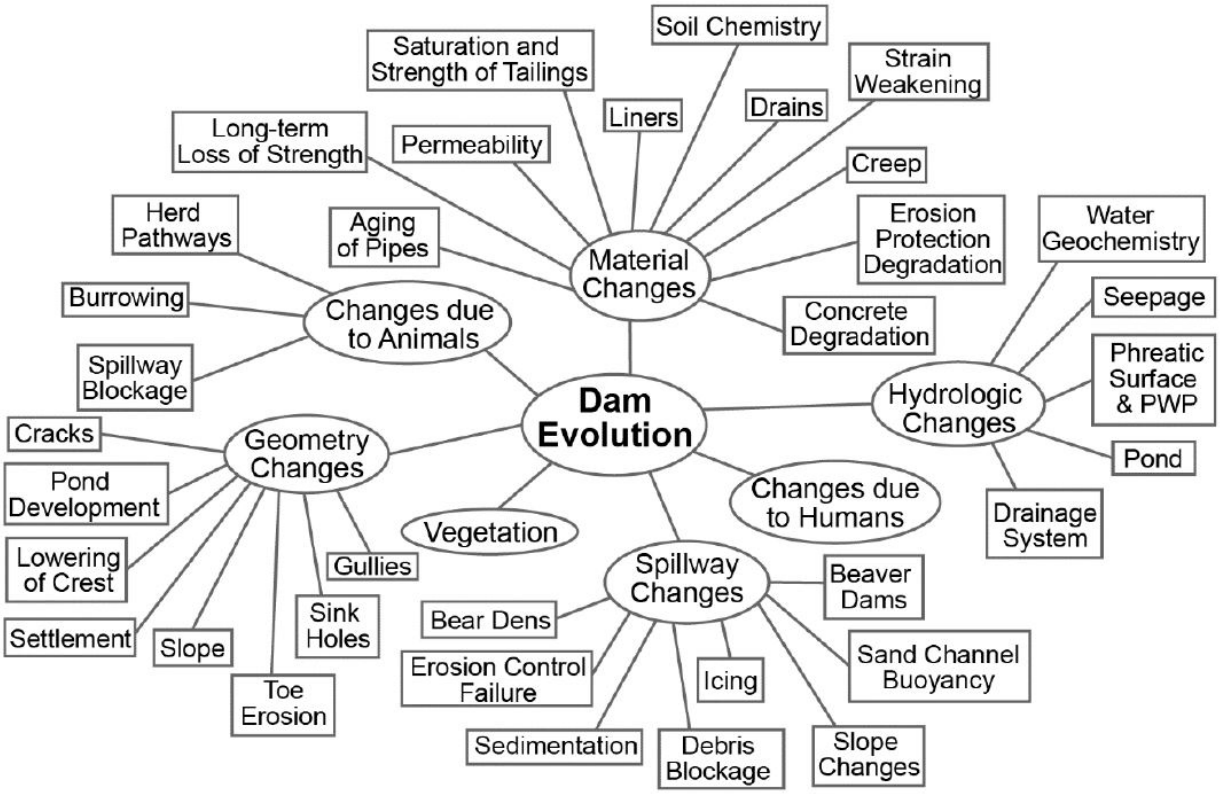


Figure 2-4: Dam features that may evolve over time (Schafer et al., 2019).

3. Tailings dam behaviour is highly site-specific.

   Every tailings dam has its own unique site characteristics, design and operational conditions (Chovan et al., 2021), type of mine and disposal method (Berghe et al., 2011). These differences present various forms and levels of risk. The failure modes in tailings dams are site-specific (Schafer et al., 2020), and therefore require site-specific information. As tailings materials are not natural soils and are produced from different ore materials and even variations in processing, they may behave differently, have different physical properties, different chemical contents, and different depositional processes among sites. These site-specific physical and chemical characteristics contribute to shaping performance and risk management (MAC, 2017).Consequently, this limits the information that can be shared among sites to potentially reduce AI and QAI uncertainties. . It means that there is uncertainty in using information from nearby sites to estimate some parameters.

4. Unlike water dams, tailings dams have an overlapping design-construction-operation sequence, occurring at the same time and iteratively.

Tailings dams' life cycle phases consist of project conception and planning, design, initial construction, operation and ongoing construction, closure, and post-closure (MAC, 2017). Risk assessments are required at the beginning of each phase and repeated periodically (MAC, 2017). Definitions of tailings dams' life cycle phases, and their characteristics associated with the responsibility of phase of risk assessment implementation, are summarized in Table 2-1after MAC (2017).

Table 2-1:Tailings dams' life cycle phases and the responsibility of risk assessment implementation

Name	**Definition**	**The team has responsibility of risk assessment**
Project Conception and Planning	Conception and planning for the mine site, such as locations for the tailings dams and best practice tailings management technology.	A multidisciplinary team* of specialists managed by the overall project development team assigned by the owner. *e.g., engineers, geologists, environmental and social scientists.
Design	Detailed engineering designs for all aspects of the tailings facility.	Professional staff experienced in the disciplines required to design the tailings facility managed by the overall project development team assigned by the owner.
Initial construction	Structures and infrastructure need to be in place before tailings deposition starts. Initial construction involves removing vegetation and overburden, and constructing	Construction management team is managed by the overall project development team assigned by the owner.

	starter dams, tailings pipelines, and access roads.	
Operations and ongoing construction	Tailings are transported, and deposition starts in tailings facilities. Tailings dams may be raised. Operating phase may be longer or shorterthan anticipated in the design phase. Suspensions and subsequent re-starts. Uncertain future operation and maintenance. Standby care and maintenance are required.	Site operators were assigned at the beginning of the commissioning of the mine development.
Closure and post-closure phases	Closure: Starts when tailings are no longer deposited into the facility permanently. Closure involves a number of steps including removing pipelines and recontouring or revegetating tailings Post closure: Starts when decommissioning work is complete, key aspects of the closure plan have been implemented, and the mine site has transitioned to long-term maintenance and surveillance.	Specific project team takes the lead in preparing for decommissioning and closure. During the post-closure phase, responsibility for a tailings facility could transfer from the owner to jurisdictional control.

In this research, the closure phase is divided into four time frames: immediate term (0-10 years), short term (10-50 years), medium term (50-200 years) and long term (1000 years) (Schafer et al., 2021).

The life cycle phases of tailings dams can occur simultaneously and iteratively. As mine plans change, the tailings dam design, construction and operation change. The life cycle of a tailings facility is rarely a simple linear progression from one phase to the next. For example, construction activities continue throughout the operating phase of the mine because the dams are raised to accommodate increasing volumes of tailings (MAC, 2017). This means there is no line that summarizes the data of a certain element from one phase to another, which adds complexity to making predictions of behaviour.

5. Within the operational phase, tailings dams are subject to some changes not anticipated at the beginning of mine life.

   The operating phase could be longer or shorter than anticipated in the design phase and have some changes such as care and maintenance suspensions and subsequent re-starts, process and technology changes (MAC, 2017). Uncertain future operating or maintenance conditions pose uncertainty issues in risk assessment (Schafer et al.,2021, Robertson et al., 2006). This adds more complexity to understanding the dam system behaviour and the changes in certain parameters.

   A "management of change element" (APEGA, 2006) must be used in the tailings dam safety to account for the overlap between the unanticipated phases and changes in the design phase (Morgenstern, 2018). Management of change makes it possible to identify the new hazards and consider the potential change in parameters. If any new hazards are not identified, there will be an unknown increasing parameter which poses unconsidered risks.

6. The information required for long-term risk assessment is an accumulation of the full range of applicable conditions: design, construction, and operation.

   To understand how the dam structure is expected to behave, the long-term risk analysis should consider that full range of applicable conditions. The information from all three phases should be considered in the analysis to ensure that the intent of the design has been achieved and the level of deviation over time from the normal conditions is tolerable (CDA, 2013). That being said, assessing the long-term behaviour of tailings dams requires all the information from all applicable phases (the cumulative sources of the information). This results in cumulative sources of uncertainties. For example, missing the as-built record document, details on starter dam structure and way of construction significantly affect the understanding of the long-term behaviour of tailings dams (AI uncertainties). Non-detailed estimations in the design document are a cumulative source of uncertainty (QAI uncertainties).

   Another example of uncertainty accumulation from all phases is climate records. Information about climate change is critical in order to conduct a long-term risk assessment. .

Climate change may affect the hydrology system and annual precipitation. Access to historical climate records is necessary to predict the long term climate change. Without this information, the prediction of climate change for long-term assessment has high degree of uncertainty (Schafer, 2022).

AI and QAI uncertainties accumulate to reach their maximum in the risk assessment of closure and post-closure phases. The ability to manage risks and improve performance decreases through the life cycle of tailings dams due to the increase of unknowns posed by the uncertainty issues mentioned above. The uncertainties associated with risks reach the highest in the closure and post-closure phases (long-term) as there is no way to understand risks, so the risk management and performance of the structure can't be improved (MAC 2017). The earlier that the unknowns related to tailings dams behaviour are reduced, the greater the potential for success that long-term tailings hazards will be assessed and meet long-term closure objectives (MAC 2017).

7. A lack of a data management plan during the transfer of facility ownership can lead to a loss of knowledge over time.

The life cycle of tailings dams, including the closure and post-closure phases, can last for decades or centuries. Typically that means that the responsibility for the risk management of tailings dams will be incumbent upon a number of different entitites during each life-cycle phase. In other words, the team that leads the design phase may differ from the one that leads the initial construction, which will differ from the one in charge during the operations and ongoing construction phase, which will differ from those in charge during the closure phase. The change in the personnel responsible for the tailings dams can be problematic from a continuity perspective (MAC, 2017). Ensuring that the risk assessment processes and the associated adopted critical controls are consistently carried forward to the next management teams is critical to conduct an effective risk assessment (MAC, 2017). Schafer et al. (2020) identified this as the element of data management considered the most important as risk assessment moves into longer time frames, i.e., those in excess of 100 years (Schafer et al., 2020). Lack of a data management plan can lead to:

- Missing information through transition phases, such as the historical records of the facility, which may not be well documented. Losing the original design data may lead to new unknown risks (MAC, 2017). Information about the final design of the dam and as-built records (including the construction method used, raising rates, and the drainage system) is critical for identifying the recent risks of the facility and forecasting the long-term behaviour.

- Different risk philosophies and different adopted criteria to evaluate the risk. What could be considered a priority risk for one team could be less important for the other, leading to different information-gathering strategies. This highlights the importance of risk communication between the teams responsible for the facilities along the different phases and between the stockholders during the same phases

8. A poor dam safety management system (SMS) is a source of AI and QAI uncertainties.

If the elements of SMS (APEGA 2006) are conducted well, the dam safety management system (SMS) could be a source of AI and QAI uncertainties.

Examples of AI and QAI uncertainty that could arise from the poor implementation of SMS:

- Frequency of inspection

  Occasional inspections lead to outdated data. Conducting inspections at irregular intervals leads to a gap in seasonal changes records, water level management databases, and records about changes in visual observations of any anomaly. Ineffective water management through occasional inspections leads to a saturation of critical zones within tailings dams which pose uncertainty in the parameters adopted for analysis.

- Deterioration in instrumentation and risk reduction measures

  Examples of this are the deterioration of some field instruments (e.g., piezometers and slop inclinometers) which originally installed through the design and operation phases.An example of erosion reduction measures deterioration is anold drains with closed outlets. Continued maintenance and repair are critical for reliable information to be obtained from instruments. The deterioration of some elements means that risks have to be reconsidered.

- Non-detailed estimations in design are a source of uncertainty

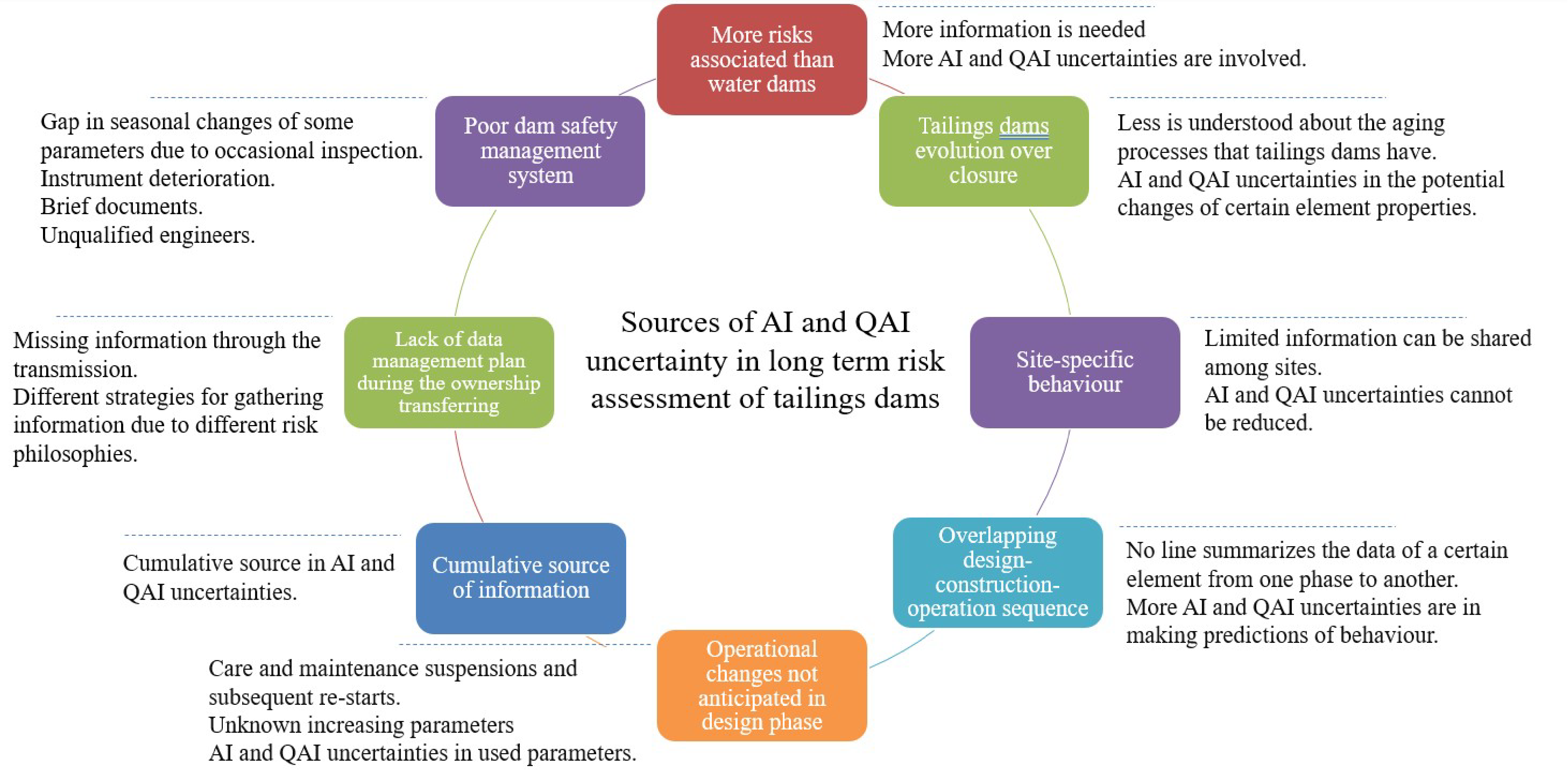
  Brief reports and documents which omit important details ultimately become a source of uncertainty. The detailed documentation for each phase of a tailings dam's life cycle is critical for minimizing the uncertainty in the risk estimation.

- Engineer of record could be a source of AI or QAI uncertainty issues

To ensure the safety of a tailings facility, the owner is responsible for identifying and retaining an engineer of record (EOR), who provides technical direction on behalf of the owner. Dam safety inspections and associated reports prepared by non-qualified engineers are not reliable sources of information.

Fig. 2-5 shows summarizes the issues that pose AI and QAI uncertainties in tailing dams.

Tailings facilities change considerably over their life cycle (MAC, 2017). It is critical to perform risk assessments to examine these changes. . Missing, outdated, and unreliable information poses an unquantified long-term risk and leads to a gap in our ability to design a successful closure of these structures, which can result in financial liability to the province. Understanding and limiting the risk inherent in closing a tailings dam are now recognized as priorities for achieving an acceptable risk tolerance for people and the environment.



More information is needed
More AI and QAI uncertainties are involved.

Less is understood about the aging processes that tailings dams have.
AI and QAI uncertainties in the potential changes of certain element properties.

Limited information can be shared among sites.
AI and QAI uncertainties cannot be reduced.

No line summarizes the data of a certain element from one phase to another.
More AI and QAI uncertainties are in making predictions of behaviour.

Care and maintenance suspensions and subsequent re-starts.
Unknown increasing parameters
AI and QAI uncertainties in used parameters.

Cumulative source in AI and QAI uncertainties.

Missing information through the transmission.
Different strategies for gathering information due to different risk philosophies.

Gap in seasonal changes of some parameters due to occasional inspection.
Instrument deterioration.
Brief documents.
Unqualified engineers.

Figure 2-5: Sources of AI and QAI uncertainties affect the confidence in the long-term risk assessment of tailings dams

3. Incorporation of Uncertainty in the Estimated Risk: Level of Confidence Framework

Consideration of confidence in estimated risks is not a new or innovative task. However, there is limited literature on detailed confidence frameworks that adequately include the special characteristics of tailings dams over the closure and post-closure phases where a dam evolves significantly over time (Schafer et al., 2019, 2020). The gap in our understanding regarding how a tailings dam ages in perpetuity (Schafer et al., 2021) leads to increasing uncertainties regarding the quality of information and its availability(AI , OAI) as the risk assessment moves from the immediate-term to the long-term timeframe of closure for some failure modes. Consequently, the development of a confidence tool to support a risk assessment is critical for assessing the long-term behaviour of dams. Ignoring the confidence in the long-term estimated risk in the presence of AI and QAI uncertainties can lead to unconsidered high risks, or/and a false interpretation of risk.

The level of confidence (LOC) framework is a tool developed in this study to allow the incorporation of uncertainty in the risk assessment process. The uncertainty issues that affect confidence in the estimated risk were identified and assessed in a comprehensive but simple manner, thereby making it readily applicable for use by practitioners.

The confidence level, for the purpose of this research, is defined as how close we expect to get to the same risk estimation (same likelihood, same consequence) if more information is available with fewer AI or QAI uncertainties. The confidence level assesses how much the risk score reflects the reality.

The LOC framework includes three major steps. First, the LOC table was developed to present a descriptive categorization of the AI and QAI uncertainties in the information used in the risk assessment and translate these into confidence levels in the estimated risk. The confidence levels were scored as high, medium, low and very low. Then a risk assessment tool was extended to include the confidence level table. The FMEA tool adopted in this research was developed by Schafer et al. (2021) to incorporate the tailings dams' characteristics and time element into the risk assessment.

3.1. Step 1: LOC Table Development

The work published by Silva et al. (2008) was used as a foundation for the development of the LOC framework. Silva et al. (2008) presented a semi-empirical relationship between the level of engineering, factor of safety, and probability of slope failure based on data from real world earth structure projects, including dams. The framework in Silva et al. (2008) was developed through quantified expert judgment and consists of two main tools: level of engineering (Table 3-1) and the relationship between the factor of safety and probability of slope failure (Figure 3-1).

The level of engineering assesses the confidence in geotechnical engineering along the life cycle phases of conventional earth structures such as slopes, earth retaining structures, and dams. Confidence in earth structure engineering is driven by the uncertainty in our design, construction, operation, and monitoring, which is associated with how much reliable resources are used through each phase. The more reliable resources that are used in mitigating or accounting for the uncertainties, the higher the level of engineering we need, which ultimately reflects safer structures. The following section will describe how the LOC table will be developed for use in the long-term risk assessment of tailings dams. After describing the levels of engineering in Silva et al. (2008) , these levels will be correlated to confidence levels in terms of AI and QAI uncertainties.

The level of engineering table consists of five categories from best (Category I) to poor (Category IV).

- Category I The facilities in this category use the most reliable resources—i.e., the highest level, state-of-the-art engineering. The facilities in this category have high failure consequences in general.
- Category II (Above Average)

  This facilities in this category use standard engineering. Most of the ordinary facilities fall into this category.
- Category III (Average)

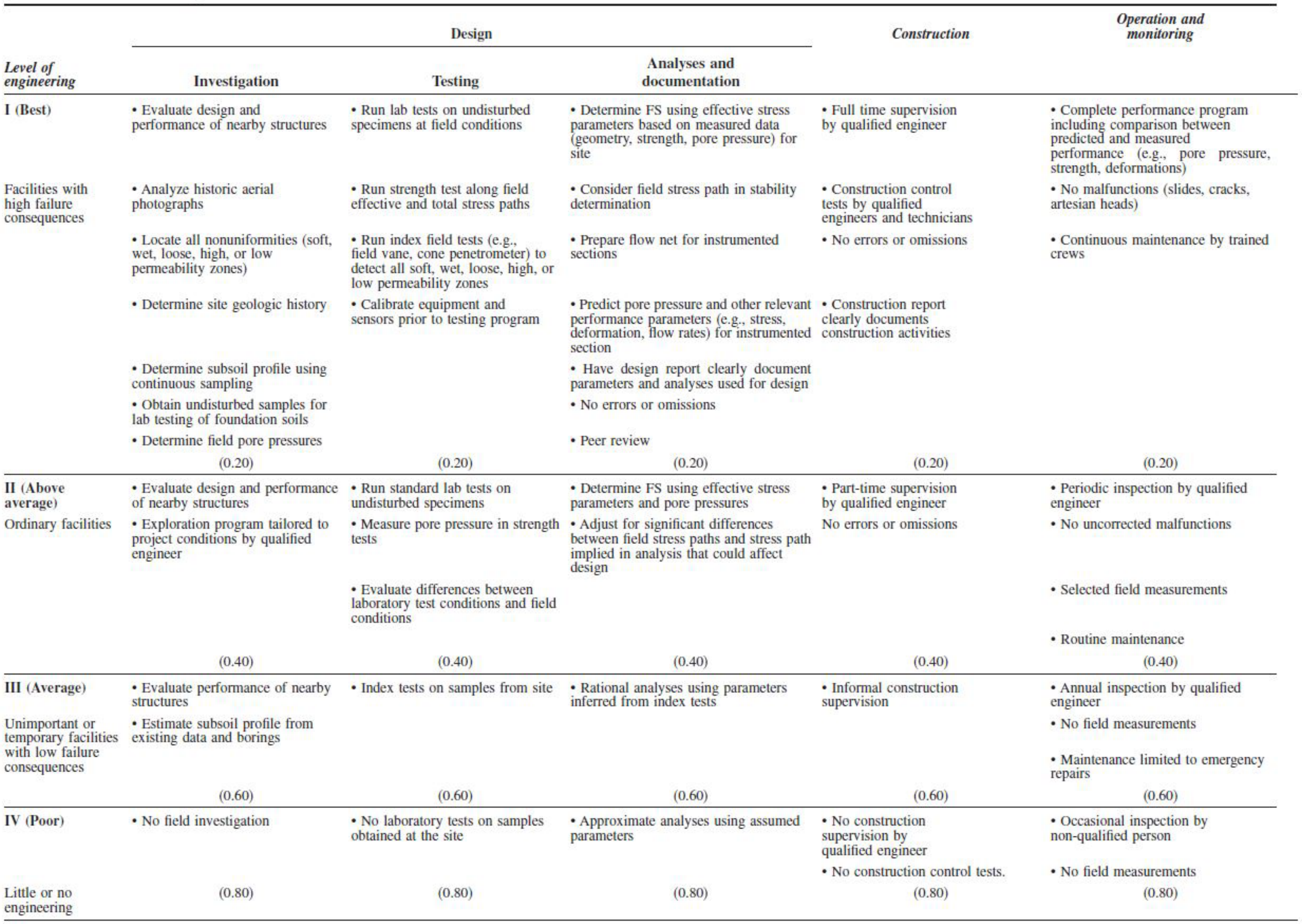
  The facilities in this category use engineering without site-specific design.

  These tend to be facilities that are built temporarily and have a potential low failure consequence.
- Category IV (Poor)

Facilities in this category use little or no engineering.

The level of uncertainty varies noticeably between categories based on the techniques or methods used by engineers to obtain the information through the whole life cycle of geo-structures. The characteristics of these categories were developed by examining the practices followed for the different phases of a project: design (investigation, testing, analyses, and documentation), construction, and operation and monitoring. The table gives an equal weighted score for each phase based on the category. For example, each phase from Category I is given an equal weight score of 0.2 and summed overall to equal one. Category IV has a score of 0.8 for each phase and the overall score is equal to four. These weighted scores help to estimate the overall score for the level of engineering and interpolate between the curves in the factor of safety and probability space.

Table 3-1:Earth Structure Categories and Characteristics according to level of engineering (Silva et al., 2008)



	Design			***Construction***	***Operation and monitoring***
Level of engineering	**Investigation**	**Testing**	**Analyses and documentation**		
I (Best)	• Evaluate design and performance of nearby structures	• Run lab tests on undisturbed specimens at field conditions	• Determine FS using effective stress parameters based on measured data (geometry, strength, pore pressure) for site	• Full time supervision by qualified engineer	• Complete performance program including comparison between predicted and measured performance (e.g., pore pressure, strength, deformations)
Facilities with high failure consequences	• Analyze historic aerial photographs	• Run strength test along field effective and total stress paths	• Consider field stress path in stability determination	• Construction control tests by qualified engineers and technicians	• No malfunctions (slides, cracks, artesian heads)
	• Locate all nonuniformities (soft, wet, loose, high, or low permeability zones)	• Run index field tests (e.g., field vane, cone penetrometer) to detect all soft, wet, loose, high, or low permeability zones	• Prepare flow net for instrumented sections	• No errors or omissions	• Continuous maintenance by trained crews
	• Determine site geologic history	• Calibrate equipment and sensors prior to testing program	• Predict pore pressure and other relevant performance parameters (e.g., stress, deformation, flow rates) for instrumented section	• Construction report clearly documents construction activities	
	• Determine subsoil profile using continuous sampling		• Have design report clearly document parameters and analyses used for design		
	• Obtain undisturbed samples for lab testing of foundation soils		• No errors or omissions		
	• Determine field pore pressures		• Peer review		
	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
II (Above average)	• Evaluate design and performance of nearby structures	• Run standard lab tests on undisturbed specimens	• Determine FS using effective stress parameters and pore pressures	• Part-time supervision by qualified engineer	• Periodic inspection by qualified engineer
Ordinary facilities	• Exploration program tailored to project conditions by qualified engineer	• Measure pore pressure in strength tests	• Adjust for significant differences between field stress paths and stress path implied in analysis that could affect design	No errors or omissions	• No uncorrected malfunctions
		• Evaluate differences between laboratory test conditions and field conditions			• Selected field measurements
					• Routine maintenance
	(0.40)	(0.40)	(0.40)	(0.40)	(0.40)
III (Average)	• Evaluate performance of nearby structures	• Index tests on samples from site	• Rational analyses using parameters inferred from index tests	• Informal construction supervision	• Annual inspection by qualified engineer
Unimportant or temporary facilities with low failure consequences	• Estimate subsoil profile from existing data and borings				• No field measurements
					• Maintenance limited to emergency repairs
	(0.60)	(0.60)	(0.60)	(0.60)	(0.60)
IV (Poor)	• No field investigation	• No laboratory tests on samples obtained at the site	• Approximate analyses using assumed parameters	• No construction supervision by qualified engineer	• Occasional inspection by non-qualified person
				• No construction control tests.	• No field measurements
Little or no engineering	(0.80)	(0.80)	(0.80)	(0.80)	(0.80)

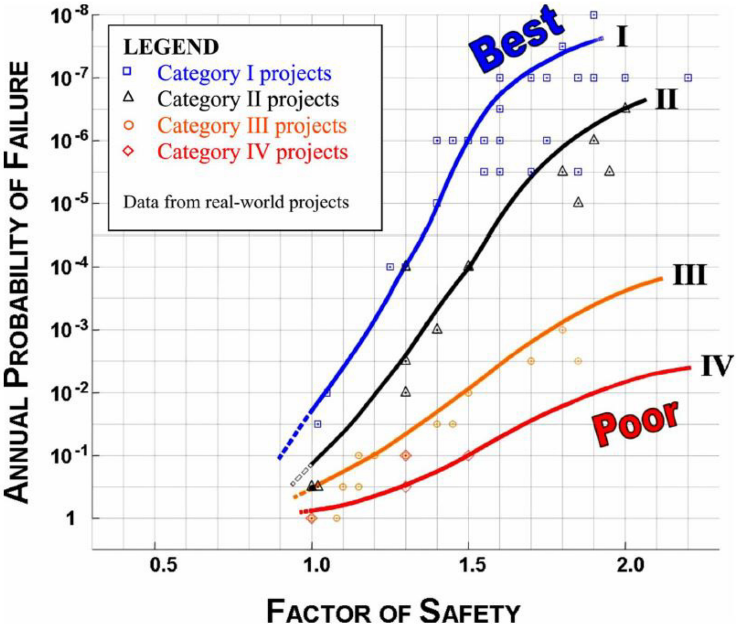


Figure 3-1: Factor of safety versus annual probability of failure (Silva et al., 2008)

In practice, the category of a specific geo structure is often interpolated between curves by summing different values for different characteristics.

Example: a particular geo structure meets most of the Category I criteria but with part-time supervision in construction.

The weighting score number for the interpolated category is shown below:

Phase 1: Design (investigation 0.2, testing 0.2, analysis and documentation 0.2)

Phase 2: Construction 0.4

Phase 3: Operation 0.2

Interpolated Category 1.2.

Then a linearly interpolated curve located 20% of the distance between Curves I and II is used.

This framework provides a relatively modest effort to estimate the slope failure probability and shows how the level of engineering can affect these probabilities. Two separate structures may have the same factor of safety, but the probability of failure may be different based on how much uncertainty there is in the information (reflected by level of engineering) when estimating the factor of safety.

To utilize Silva's categories in the long-term risk assessment of tailings dams, adjustments are required. The categories and their characteristics from Silva et al. 2008 need to be expanded to reflect a specific earth structure such as tailings dams. Research by Morgenstern (2018) and Oboni (2020) was used as a basis for customizing the table in Silva et al. for tailings dams. It was also used to consider the sources of uncertainties in terms of the AI and QAI discussed.

Morgenstern (2018) outlined recommendations on how to increase confidence in the safety performance of tailings dams. The framework presents a systematic approach to decreasing the uncertainty early in each phase. This framework is known as the performance based, risk informed safe design, construction, operation and closure (PBRISD) of tailings dams. The PBRISD recommendations are used as a base to represent and customize Category I in Silva for tailings dams. Table 3-2 shows the PBRISD framework summarized by Macciotta and Lesfrud (2020) after Morgenstern (2018).

Table 3-2: PBRISD framework summarized by Macciotta and Lesfrud (2020) after Morgenstern (2018).

Phase 1 – Conceptual Design
• Selection of qualified engineer – requirements for qualified engineer
• Allocation of responsibilities – organizational chart requirements
• Facility classification and review requirements – main input associated with location and technology, classified according to consequence, precedent and complexity/review requirements associated with the classification
• Review boards – set of characteristics for review board members, procedures, documentation/confidentiality and handling of information
• Design basis memorandum – tied to design philosophy (risk-based, performance-based). Reflects sources of uncertainty, explicitly stating uncertainty levels for design models (e.g., geology, hydrogeology, geomechanical, mechanical)
• Multiple Accounts Analysis (MAA) of conceptual option – process description for option evaluation/ documentation/information handling
• Risk evaluation of conceptual options – process failure modes and effects analyses (PFMEA)/risk registers/other tools/assessment and selection of conceptual design
• Uncertainty evaluation – evaluate sources of uncertainty/priority ranking of uncertainties (in combination with

MAA and PFMEA outcomes)
Phase 2 – Detailed Design • Engineer of Record (EOR) qualifications • Allocation of responsibilities – organizational chart requirements • Review boards – set of characteristics for review board members, procedures, documentation/confidentiality and handling of information • Design components checklist – set of required checks such as physical stability, geochemical stability, probable maximum floods and water balances, filter design specifications, etc. • Design documentation – required documentation • Design reviews – update of PFMEA and uncertainty levels. Are these adequate? Where to focus efforts? At 25% and 75% design?
Phase 3 – Final Design for Construction • Documentation for construction – construction specifications and drawings/contracts/supervision • Allocation of responsibilities – organizational chart requirements • Review boards – set of characteristics for review board members, procedures, documentation/confidentiality and handling of information • PFMEA prior to investment • Operation, maintenance and surveillance manual (OMS) • Detailed QA/QC program – OMS and QA/QC program to ensure protocols are sufficient to demonstrate that the intent of the design is met during construction/adequacy of the program
Phase 4 – Operation • Safety Management System (SMS) during operations (OMS manual) – key components of the OMS manual/ required documentation and review/can discuss some elements • Management of change – particularly affecting original design intent • Auditing and reviews – focus/documentation and information management • Allocation of responsibilities – organizational charts/accountability
Phase 5 – Detailed Closure Design and Implementation • Design engineer qualifications • Allocation of responsibilities – organizational chart requirements for closure • Review boards – set of characteristics for review board members, procedures, documentation/confidentiality and handling of information for the closure stage • Performance-based approach to closure • Closure safety evaluation – based on as-built and closure design/FMEA for potential scenarios/performance • Closure and post-closure documentation and review – document and information handling of monitored performance/reviews

Oboni and Oboni (2020) categorized the practical management of tailings dams in a portfolio of four dams which they named Dam 1, 2, 3, and 4. This portfolio was built based on real-life tailings dams belonging to different clients around the world and used in this research as a base of customizing the level of the Silva et. al (2008) engineering table for tailings dams. Detailed characteristics of these dams are categorized according to the following criteria: construction, geotechnical investigation and testing, analysis and documentation, stability analysis, operation and monitoring, and maintenance and repair.

Oboni (2020) assessed the portfolio of the four tailings dams using the Silva method and determined the level of engineering category for each dam. The tailings dams portfolio and dam characteristics are summarized in Table 3-3 and associated with the category that yields from application of the method in Silva et al. (2008).

Table 3-3: portfolio of tailings dams associated with category yields using Silva's methods. After Oboni (2020).

Tailings dams	Construction	Geotechnical investigation and testing	Analysis and documentation	Stability analysis	Operation and monitoring	Maintenance and repair	Category according to Silva et al. (2008) estimated by Oboni and Oboni (2020)
Dam 1 Centerline-rockfill tailings dam analyzed at two stages.	• Non-erodible by assumed extreme meteorological conditions. • Pipeline and traffic at crest. • Excellent supervision of the dam in terms of frequency and in terms of the supervisor's skills. • No geometric divergences were noted between the plans and the actual structures - minor intermittent seepage was monitored at one location at the toe. • There were no known errors or omissions in this project according to third-party competent independent reviewers.	• Boreholes along the dam layout were regular. However, at less than 1/100 m, they were rather short, barely entering the bedrock. • No continuous sampling was performed. • Vane tests and cone tests were numerous but poorly distributed due to limitations of access. • Soil classification tests were performed in a reasonable number and at a reasonable frequency. • Geomechanical tests were numerous and distributed. • A significant number of residual strength, odometer, and triaxial tests were performed.	• The project was deemed to be of good quality by a competent engineering firm and a skilled team. • The "as built" plans display no significant imperfections and variations. •The alteration plans were also regularly updated.	• Effective and pseudostatic stability analyses were performed by the engineers. • Settlement analyses were performed. • Liquefaction was dismissed by the engineers and is agreed to be dismissed • Engineers analyzed internal erosion and determined it was not a problem	•Pore pressure was measured with numerous vibrating wire piezometers. • Deformations were monitored by topographic observations and inclinometers. • Independent Geotechnical Review Board (IGRB) was active. • A reputatble third-party conducts annual inspections.	Repairs were carried out in a timely manner when damages were identified during the inspection.	**1.4 - 1.6**

	Construction	Geotechnical investigation and testing	Analysis and documentation	Stability analysis	Operation and monitoring	Maintenance and repair	Category according to Silva et al. (2008) estimated by Oboni and Oboni (2020)
Dam 2 Water retention centerline dam built in one raise with selected materials.	•Non-erodible by assumed extreme meteorological conditions. • No pipeline at crest. • Supervision of the dam was mediocre in terms of both frequency and the skills of the supervisor. • Some locally significant geometric divergences have been noted between the plans and the actual structures and minor intermittent seepage is being monitored at one location at the toe. • There are no known errors or omissions in this project, according to third-party competent independent reviewers.	•There were only a few boreholes along the dam layout (fewer than 1/100 m); they were at least as deep as the structure was high. • No continuous sampling was performed, but 15 trenches were dug, although they were poorly distributed along and across the layout. • Vane tests and cone tests were numerous but poorly distributed due to limitations of access. • A reasonable number of soil classification tests were performed at a reasonable frequency. • Geomechanical tests were limited and poorly distributed. • Very few residual strength, oedometer and triaxial tests were performed.	•The project is deemed to be of good quality by a competent engineering firm and a skilled team. • The "as built" plans display some significant imperfections and variations. • The alteration plans also have some significant approximations.	•Effective drawdown and pseudostatic stability analyses were performed by the engineers. • No settlement analyses were performed. • Liquefaction was dismissed by the engineers and engineers agreed to dismiss. • Engineers analyzed internal erosion and determined it was not a problem	•Pore pressure was measured with six vibrating wire piezometers. • Deformations were monitored by topographic observations. • There was no active IGRB. • A reputable third party conducts annual inspections.	No repairs are carried out when damages are identified during the inspection.	**2.2-2.4**

	Construction	Geotechnical investigation and testing	Analysis and documentation	Stability analysis	Operation and monitoring	Maintenance and repair	Category according to Silva et al. (2008) estimated by Oboni and Oboni (2020)
Dam 3 Raises are upstream, made of compacted crushed rock, on tailings.	• Engineering studies have determined the berms (raises) were non-erodible by extreme meteorological conditions or even by a breach of the tailings pipeline. • Supervision of the dam was of good quality in terms of both frequency and the skills of the supervisor. • Minor geometric divergences were noted between the plans and the actual structures. Minor intermittent seepage was being monitored at one location at the toe of the starter berm. • There were no known errors or omissions in this project, which has been third-party reviewed by competent independent reviewers.	• There were only a few boreholes along the dam layout (fewer than 1/100 m); they were generally short (the engineers said that the rock was of a sound nature and they didn't expect to find any weakness), barely penetrating into the assumed bedrock. • No continuous sampling was performed. • Penetrometers, vane tests and cone tests were numerous but poorly distributed due to limitations of access. • A reasonable number of soil classification tests were performed at a reasonable frequency. • Geomechanical tests were numerous but poorly distributed. • A limited number of residual strength, odometer and triaxial tests were performed.	• The project was deemed to be of good quality by a competent engineering firm and a skilled team. • The "as built" plans displayed some imperfections and variations. • The alteration plans also had some approximations.	•Effective, undrained and pseudostatic stability analyses were performed by the engineers. • No settlement analyses were performed. • Liquefaction was dismissed by the engineers. Without proof we considered this a likely event due to the dam's construction and the material underlying the raises. • Engineers analyzed internal erosion and determined it was not a problem. the internal erosion is considered again given surface observations.	• Pore pressure was measured using more than 20 vibrating wire piezometers. • Four inclinometers were regularly read (although they were too short in our opinion). • The IGRB was active and competent. • A reputable third party conducts annual inspections.	Some repairs were carried out when damage was identified during the inspection and after the IGRB discussed the repairs.	**1.6-1.7**

Dam 4 Upstream dam of obsolete design similar to recently failed dams.	Construction	Geotechnical investigation and testing	Analysis and documentation	Stability analysis	Operation and monitoring	Maintenance and repair	Category according to Silva et al. (2008) estimated by Oboni and Oboni (2020)
	In the process of deactivation, so there were no active pipelines at its crest. There was vehicular and subcontractor traffic at the crest of all of the dams.		• Slopes were steeper than designed. • Failure was incipient toward the Eastern abutment;	• There was uncontrolled erosion of the downstream (D/S) slopes.	• There was a monitoring system, but limited information regarding the readings, frequency, etc.		**3.3-3.8**

In this research, adjustments were applied to the framework of Silva et al. (2008). These adjustments are explained as follows:

1. Adjustment 1 - Add new phase (closure phase) and develop the criteria based on recommendations from the PBRISD framework.

   The Silva et al. (2008) categories consider characteristics for conventional geotechnical structures which have three distinct phases: design, construction, and operation. These categories have been adjusted to account for the life cycle phases of tailings dams, which have closure and post-closure phases. The first adjustment was to add a new phase (closure phase). The new characteristics for this phase were expanded from Silva et al. (2008) based on the PBRISD framework (Morgenstern, 2018) and the Oboni and Oboni (2020) criteria for tailings dams (Oboni, 2020). As the closure phase can extend to decades or centuries, it is important to consider the dam evolution over time through the closure phase criteria. The criteria considered for the new added closure phase were.

   1. Continuous physical and chemical site investigation and testing
   2. Climate change records.
   3. Quarterly inspection
   4. Maintenance and repairs
   5. Instrumentation and risk reduction measures deterioration check
   6. Quality assurance and quality control programe (QA/QC)
   7. Closure documentation meeting the standards for dam and environment safety
   8. EOR for closure design and safety evaluation
   9. Independent Review boards (IRB)
   10. Data management through the transferring of the facility ownership and risk communication between stakeholders.
2. Adjustment 2 - Customize and expand the characteristics alongside the other phases in the Silva table to account for more tailings dams practices.

   The PBRISD recommendations (Morgenstern, 2018), along with Oboni tailings dams portfolio (Oboni, 2020), were used as a base. The phases' criteria for tailings dams adapted in this research are described in detail below after Silva et al. (2008)

1. Design
   1.1. Level of field investigation

   1.2. Testing used to estimate the parameters
   1.3. Documentation
2. Construction
   2.1. As-built record
   2.2. QA/QC program
   2.3. Supervision of EOR
   2.4. IRB
3. Operation
   3.1. Continued field measurement
   3.2. Water management level database
   3.3. OMS manual (OMS)
   3.4. Frequency and date of inspection(s) during the year to account for seasonal changes
   3.5. Level of detail in inspection report, such as seasonal changes and records of changes of visual observations
   3.6. EOR
   3.7. IRB
4. Closure and post-closure phases
   4.1. Conducting investigation and sample tests over time including physical and chemical field investigations
   4.2. Climate change records
   4.3. Frequency and date of inspection(s) during the year to account for seasonal changes.
   4.4. Level of detail in inspection report, such as seasonal changes and records of changes of visual observations. Documentation meeting the standards for dam and environmental safety.
   4.5. Maintenance and repairs
   4.6. Status of instruments and risk reduction measures (destruction of vegetation cover, deterioration of piezometers)
   4.7. QA/QC
   4.8. EOR
   4.9. IRB

4.10. Data management through transferring facility ownership and risk communication between stakeholders

For the design and construction phases for the closure plan, Criteria 1 and 2 can be adopted

3. Adjustment 3 – New weighting score for Adjustments 1 and 2

   Silva et al. (2008) gave an equal weighted score for each phase based on the category assessed. As a new closure phase was added, a modified score was considered for all phases (design, construction, and operation) and a higher score considered for closure as it is the main focus for long term-risk assessment. The total sum of each category was the same, to be consistent with the factors of safety and annual probability of failure figures according to Silva et al. (2008). This assumed that the time component would not influence the relationship between the factors of safety and probability of failure. It was acknowledged that the very long periods of time considered for closure were a significant extrapolation of the design lives of the structures evaluated to develop the method in Silva et al. (2008). However, it was a best approximation with the data available and can be updated as we learn more about the performance of closed facilities.

Table 3-3 shows the LOC table developed. This table consists of LOCs in the long-term risk assessment of tailings dams in terms of AI and QAI categories associated with characteristics for the adapted criteria.

Table 3-4 shows the weighting score in Silva et al. (2008) and the modified one used in this research. Table 3-5 shows the levels of confidence definition for the purpose of this research.

Table 3-3: Confidence levels in risk assessment through the life cycle of tailings. After Silva et al. (2008)

(AI and QAI) Categories	Level of Uncertainty	Level of Confidence	Characteristics
Category I (Best)	Low	High	1. Extensive site investigation program to better understand the geological complexity of the site for soils and rock formations. Determine subsoil profile using continuous sampling. Advanced laboratory testing on undisturbed

			specimens at field conditions. Consider field stress path and field pore pressures to determine the parameters of soils. Detailed QA/QC program for field investigation and testing. Design assumptions are well documented with no omissions. EOR qualifications. IRB – set of design characteristics, procedures and documentation for review board members. 2. Detailed as-built records for the starter dam and construction method with no omissions and well-established methodology including all construction levels, types, and frequency of QC and QA. Engineer of records EOR) is recognized by having qualified engineers provide full-time supervisionProvide a set of all construction levels for independent review board members. 3. Periodic field measurements during the ongoing construction and operation. Managing the change system to evaluate and adapt to all changes posed by overlapping operation and construction. Developed and fully documented water balance and water management plans. Periodic updates of OMS through quarterly inspections by qualified engineers (EOR). Conduct(ed) seasonal changes. The inspection report clearly documents inspection methodology, activities, observations and straightforward procedures. Changes were recorded in the case of unusual observations. Provide a set of detailed OMS for independent review board members. 4. Continuous comprehensive site investigation and tests for more understanding of all potential physical and

			geochemical changes of dam properties over time. Detailed QA/QC programs for field investigation and testing. Historical climate records are available from in-site stations with daily resolution. Performance-based approach to closure and regular updates of risk assessment for both dam and environmental safety. Closure design plan is refined. Sensitivity analysis is conducted for potential changes in conditions. Detailed as-built and closure design document meets the standards for landform and environmental safety. Quarterly inspections conducted by qualified engineers (EOR). Continuous maintenance by trained crew. State of the art instrumentation, periodic checks for deterioration. New instruments were installed which are adequate for the closure phase.Provide a set of closure design characteristics, procedures, and documentation for independent review board members. Data management transfer plan is/was? conducted and there was/is no gap in risk communication.
Category II (Above average)	Moderate	Moderate	1. Targeted, basic geotechnical investigation. Geological information follows/ed basic standards and international specifications. Design and performance of nearby structures is/was evaluated. Laboratory testing on disturbed samples from continuous samplers was/is correlated with index testing. The pore water condition from strength tests was/is estimated. Parameters are/were assumed for the special layers based on experience and using empirical correlations. A QA/QC program for field investigation and testing have/had some omissions, resulting in uncertain issues. Detailed design assumptions are/were documented with omissions. EOR qualifications were/are met. Provide

			a brief set of design characteristics, procedures and documentation for independent review board members. 2. As-built records for the starter dam and construction method were/are detailed, with omissions. Some original references to the construction stage are/were not available for the new regulator or independent technical review board. QA/QC programs for all construction stages with omissions result/resulted in uncertain issues. EOR provided part-time supervision by qualified engineers.provide a brief set of construction stages for independent review board members. 3. Field measurements selected during the ongoing construction and operation. Some level of water control management information. Biannual update of an OMS manual through biannual inspections by qualified engineers (EOR). Detailed reports and documentation with omissions, not fully meeting the standards for Category I. IRB – set of some elements for review board members. 4. Selected site investigation. Confirm some soil parameters and their evolved characteristics based on effective monitoring and field observations. No comprehensive long-term asset management. Not in compliance with the standards for Category I. QA/QC program for field investigation and testing with omissions result in uncertain issues. Detailed as-built and closure design documents meeting the standards for landform and environmental safety with omissions. Historical climate records are

			available from regional climate stations with daily resolution. Biannual inspections by qualified engineers (EOR). Routine maintenance. IRB – brief set of as-built and design closure word missing? for review board members. Turnover rate between owners and regulators. Data management transfer plan is conducted with omissions and gap in risk communication.
Category III (Average)	High	Low	1. Insufficient site investigation. Evaluate performance of nearby structures. Estimate subsoil profile from existing data and borings of nearby structures. Index tests on samples from site. Parameters used in analysis inferred from index tests. Brief QA/QC program for field investigation and testing. Brief explanation of design assumptions is documented. Qualified engineers Provide a set of design characteristics, procedures and documentation for informal peer review. 2. Brief as-built records for the starter dam and construction method. Brief QA/QC program. Brief explanation of design assumptions is documented. Informal construction supervision by qualifies engineers. Provide a set of brief construction levels for informal peer reviewers. 3. No field measurement during the ongoing construction and operation. Annual update of an OMS manual through annual inspections by qualified engineers (EOR). Maintenance limited to emergency repairs. Brief reports and documentation. IRB – set of some elements of OMS for informal peer review.

			4. Limited site investigation conducted occasionally and after special events. High turnover rate. Some original references of design are available for the new regulator or independent technical review board. Maintenance limited to emergency repairs. Deterioration in some existing piezometers. Brief historical records of climate data from regional climate stations. IRB –set of as-built and design closure word missing? for informal peer review. Annual inspections by qualified engineers (EOR)
Category IV – Poor	Very high	Very Low	1. No field investigation. Index properties. Assumed parameters based on conceptual geology. No laboratory tests on samples obtained at the site. No QA/QC program for field investigation and testing. No qualified supervision 2. No as-built records or construction method details for the starter dam and further raises. No construction supervision by qualified engineer. No construction control tests. Engineers do not have background knowledge about dams. 3. No field measurement during the ongoing construction and operation. The inspection program is conducted occasionally and after observing anomalous behaviour of the structure. by non-qualified person. Staff in the field do not have backgrounds in dam safety. No formal documentation and reports of inspections. 4. No investigations and tests are conducted over time. High turnover rate. Original references of design consideration and construction stage are not available for the new

			regulator or independent technical review board. Limited instrumentation. Most of the instruments are old and are deteriorating. No climate records are available. Occasional inspection program by non-qualified person.

Table 3-4: Weighting score for criteria adopted in the LOC framework. After Silva et al. (2008). The first number is what Silva used and the second is the LOC

Criteria	Category I Silva/LOC	Category II Silva/LOC	Category III Silva/LOC	Category IV Silva/LOC
1. Design 1.1. Investigation	0.2/0.15	0.4/0.3	0.6/0.45	0.8/0.6
1.2. Testing	0.2/0.15	0.4/0.3	0.6/0.45	0.8/0.6
1.3. Documentation	0.2/0.15	0.4/0.3	0.6/0.45	0.8/0.6
2. Construction	0.2/0.15	0.4/0.3	0.6/0.45	0.8/0.6
3. Operation	0.2/0.15	0.4/0.3	0.6/0.45	0.8/0.6
4. Closure and post-closure	0/0.25	0/0.5	0/0.75	0/1
Silva/ LOC summing	**1/1**	**2/2**	**3/3**	**4/4**

Table 3-5: Confidence levels in the LOC framework

Confidence Level	Description of confidence level	Details of AI and QAI
High	The information used to estimate the risk has a low level of uncertainty. The risk assessment is effective according to the current best practices in geotechnical and environmental engineering.	The information used to estimate the risk of a failure mode is available. There are uncertainties related to QAI, which can't be eliminated according to current best practices in geotechnical and environmental engineering.
Medium	The information used to estimate the risk has a medium level of uncertainty. There may be a potential for unconsidered risks and/or false interpretation of some risks. More information is needed based on detailed sensitivity analysis of uncertainty for more effective risk assessment.	Most of the information used to estimate the risk of a failure mode is available. There are uncertainties related to AI and QAI. Some uncertainties can't be eliminated due to safety or financial issues.
Low	The information used to estimate the risk has a high level of uncertainty. Unconsidered risks and/or false interpretation of some risks. More information is needed based on detailed sensitivity analysis of uncertainty about more effective risk assessment.	There is a gap in theAI used to estimate the risk of a failure mode. The available information has a high level of QAI uncertainties.

Very low	The information required to estimate the risk has a very high level of uncertainty. More information is needed to start a meaningful risk assessment.	Most of the AI used to estimate the risk of a failure mode is not available. The available information has a very high level of QAI uncertainty.

The complete LOC criteria in Table 5 can be used to give an initial assessment about the data category and the associated level of uncertainty for the structure. The LOC category for a particular failure mode needs to consider those criteria that would be relevant. If criteria that is not relevant to the failure mode is considered, this could result in a misleading estimation of the uncertainty for the failure mode. For example, while the AI and QAI uncertainty in criteria such as climate change records can highly affect failure modes such as surface erosion and destruction of vegetation cover, this uncertainty should not have a major effect on other failure modes such as vertical deformation in foundation. Considering this, the subcategory 4.2 (climate records) for a vertical deformation in foundation failure mode will be deleted and the weighting score of the other relevant subcategories will be the closure weighting score divided by nine instead of 10. Two demonstration failure mode examples will be presented in Chapter 4 and the most relevant criteria and detailed calculation of the data category and level of confidence will be discussed.

3.2. Step 2: LOC Table Through a Risk Assessment Tool

The generalized FMEA tool (G-FMEA) developed by Schafer et al. (2021) was used in this research. The G. FMEA is a modified FMEA tool to be used in industry to assess the long-term risk of the failure of a tailings dam following closure, incorporating the element of time. This allows the user to account for the evolution of the system; how risk profiles may change over time due to system changes (Schafer et al., 2021). The G-FMEA was selected for the following reasons:

1. It was designed to be adequate for tailings dams characteristics and the long-term behavior of these structures, which are the focus of this research.
2. It was developed based on the current state of practice with FMEA analyses, assisted by industry experience through interviews with skilled practitioners (Schafer et al., 2019) and (Schafer et al., 2020).

3. It has an extensive and reasonably comprehensive list of failure modes for the various elements of tailings dams. This is referred to as G-FMEA charts. The applicable failure modes for a specific site can be easily identified with details about the potential triggers and failure effects.

The G-FMEA divides the overall time for the closure phase into four time frames shown in Table 3-6. The G-FMEA suggests updating the risk assessment through each of these time frames to incorporate aging processes and the dam evolving over time. The immediate-term risk assessment should occur during the adaptive management period. The short-term risk assessment may occur during the adaptive management or the proactive management period, based on site-specific characteristics. The medium-term and long-term time frames should occur during the reactive management period (Schafer et al., 2021). The adaptive management period, proactive management period, and reactive management period are outlined in Table 3-6 (B).

Table 3-6: Closure time frames for various levels of risk assessment after Schafer et al. (2021)

(A)

Risk Assessment	**Assessment Period/years**	Assessment Period/ ManagementCharacteristics
Immediate term	0-10 years	Adaptive management
Short term	10-50 years	Adaptive management / Proactive management
Medium term	50-200 years	Reactive management
Long term	1000 years	Reactive management

(B)

Assessment Period	Definition
Adaptive management	Occurs following closure activities when the closed facility may be at its greatest risk of failure prior to reaching equilibrium. The operator has the greatest capacity to respond. This period may be defined explicitly by the regulator, using accumulated knowledge, or using a site-specific scientific basis.
Proactive management	Occurs as personnel and equipment are reduced. Involves a regular fixed frequency monitoring and maintenance schedule to confirm that the landform is trending along the designed trajectory. It is expected that the frequency will be less than during the adaptive management period.
Reactive management	Issues are rectified strictly on a reaction basis, once a trigger event occurs. There should be a clear plan in place that outlines what the trigger events are and how they will be managed. Monitoring may occur in response to events such as fires, floods, earthquakes, and other extreme events.

Over the closure phase of tailings dams, it is important to account for the time element when assessing the risk, as the risk category is not constant and may change over time (Schafer et al., 2021). Figure 3-2 presents a graphical representation of the G-FMEA assumptions with examples on how the risk category can change over time for particular failure modes as summarized after Schafer et al. (2021).

Time frame A represents the state of a system in the immediate term (0-10 years), B is the short term (10-50 yeas), C is the medium term (50-200 years) and D is the long term (1000 years).

A specific failure mode with a medium risk level at time frame A can have a change in risk level as we evaluate time frames B, C and D. The risk may be assessed as being at a higher level for the same failure mode which would require a higher level of risk control measures to be implemented.

The increase in risk profile over time may be caused by one or a combination of the following reasons:

1. Time frame B

   As time progresses, one or more features of the dam undergo evolutionary processes. For example, perimeters ditch may retreat over time because of blockage due to sedimentation and a reduction in the cross section due to a slope failure in the walls. Considering the this retreating the likelihood of a specific drain failure mode may increase which poses a higher level of risk.
2. Time frame C

   As time progresses, the risk tolerance (i.e., the acceptable level of risk) may change. This may be due to an increase in the awareness of tailings dams risks; growth in residential areas near the facility; or the property ownership being transferred, which may result in different criteria being adopted for the same facility. As a result, the same likelihood and consequence of the base case in Time Frame A may result in a high rather than medium level of risk.
3. Time frame D

   As time progresses, the risk may increase due to the potential increase in the frequency of trigger events. The probability of a specific failure mode over time may therefore increase, or may result in higher consequences and ultimately in a higher level of risk. An example of this could be increases in the frequency of ongoing water contamination episodes (Amirshenava and Osanloo, 2018).

The risk profile may follow also a decreasing trajectory such as foundation failure modes, which are generally expected to have a decreasing risk over time (Schafer et al., 2019).

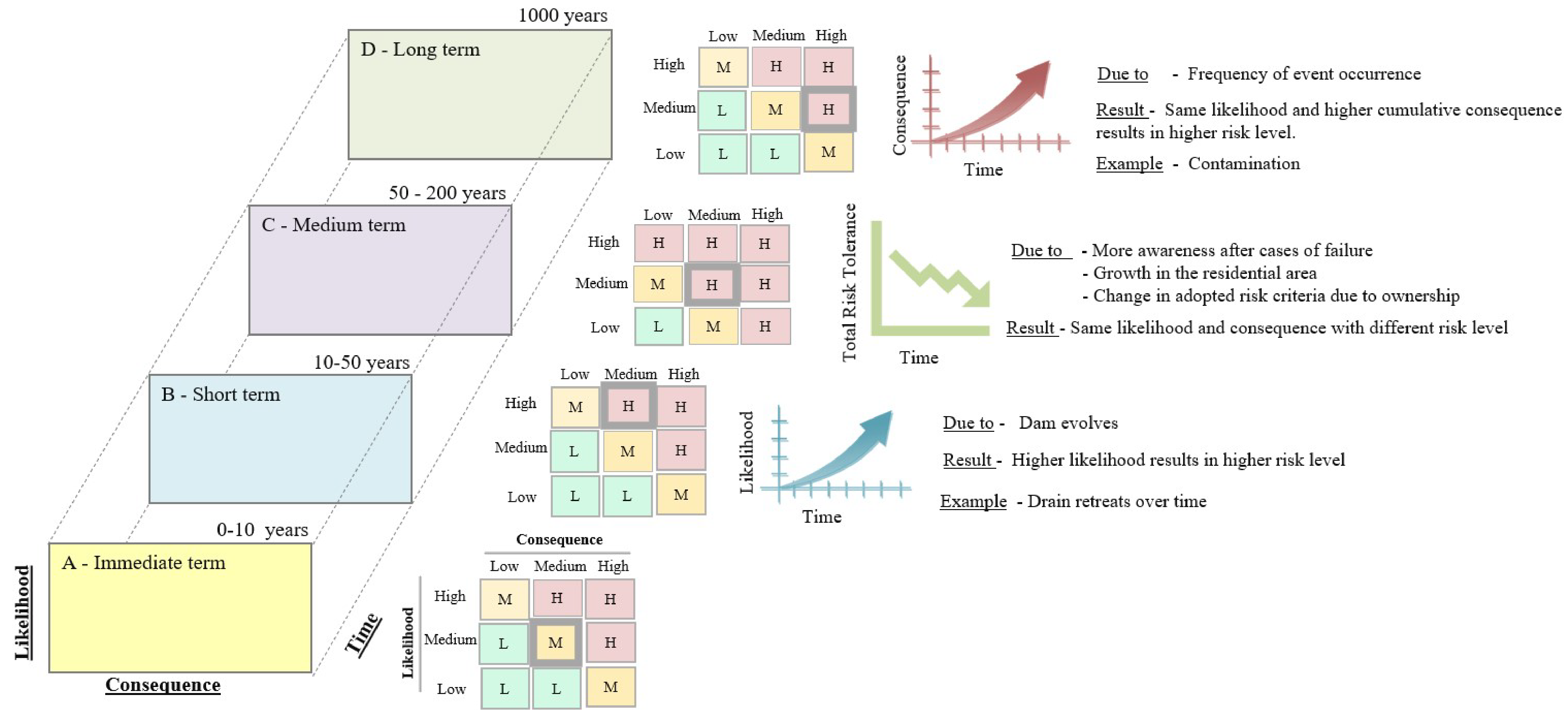


Figure 3-2G-FMEA theory after Schafer et al., 2021

The application of G-FMEA includes three main levels:

Level 1: System definition, block diagram, and key elements

This level aims to achieve a comprehensive understanding of the dam system and its components.

Level 2: Applicable failure modes

This level assesses which of the failure modes in the G-FMEA charts is applicable to the particular case study. The complete G-FMEA charts are provided in Appendix A: Generalized FMEA Charts for Various Elements of External Tailings Facilities in Alberta, which will be explained in detail in Section 3.2.2

Level 3: Risk category

Identify the risk category based on three components: likelihood, and consequences through all time frames of closure and post-closure phases (immediate, short, medium and long term).

The LOC will be integrated with the G-FMEA in Levels 2 and 3.

Figure 3-3 presents the plan followed to conduct the G-FMEA associated with the LOC framework. The detailed steps for each level in G-FMEA are explained below after Schafer et al. (2021). There is also an explanation of where and how the combination of G-FMEA with the LOC framework is conducted.

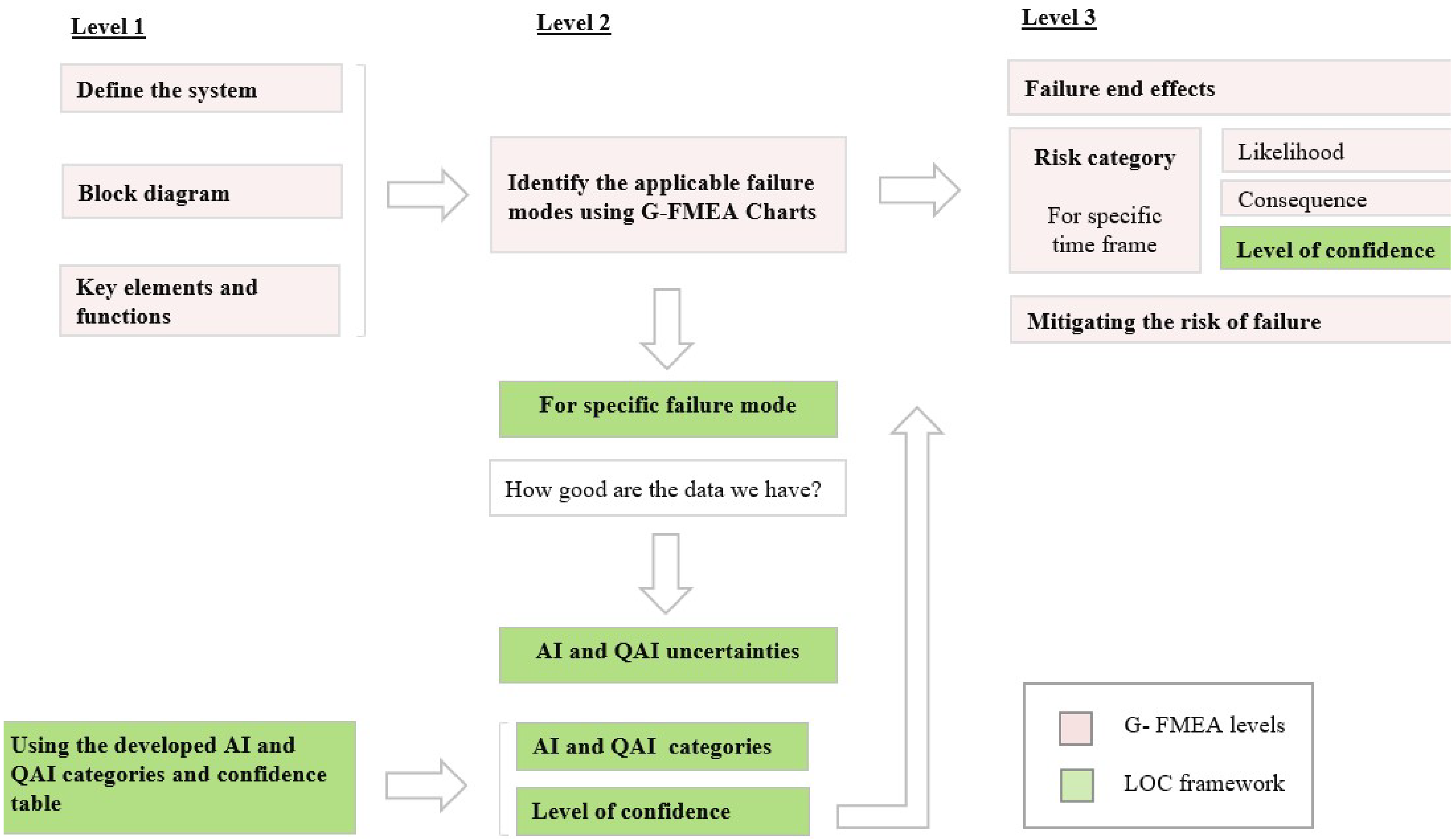


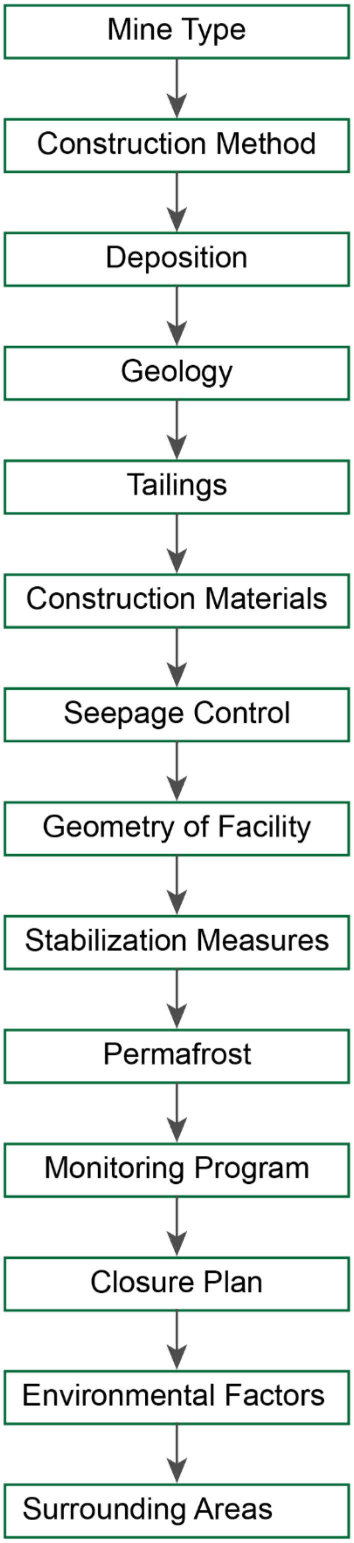
Figure 3-3:Levels of G-FMEA accompanied by the LOC framework

3.2.1. Level 1: System Definition, Block diagram and Key elements

This level consists of three components:

1. System definition
2. Block diagram
3. Key element table

The system definition step focuses on gathering information about the particular dam structure is necessary for the risk assessment process. System definition includes identifying the tailings dam characteristics that impact the tailings dam behaviour. These characteristics should be carefully considered and defined before starting the next level of the FMEA. Figure 3-4 shows the general tailings dam characteristics required before starting the long-term risk assessment of these facilities. This information is accumulated over the life cycle of tailing dams (design, construction, operation and closure and post-closure phases).



Mine Type	a) Oil sands b) Coal
Construction Method	Starter dyke (Y/N) a) Upstream b) Downstream c) Centreline d) Modified centreline e) Combination f) Unknown
Deposition	a) Hydraulic fill construction i) Spigotting ii) Cycloning with direct deposition iii) Cell construction iv) Combination b) Overburden construction c) Combination d) Unknown
Geology	Assess geology, including determination of liquefiable or brittle behaviour
Tailings	Characterize tailings, including state parameter
Construction Materials	a) Oil Sands i) Tailings ii) Interburden/overburden (i.e. lean oil sand, clay shale, till, etc.) iii) Coke b) Coal i) Interburden/overburden ii) Coarse coal refuse
Seepage Control	a) None b) Seepage reduction measures (low permeability core, grout curtain, upstream impervious blanket) c) Drains (natural materials, tailings, coke, geosynthetic, non-perforated pipe, perforated pipe, etc.) i) Chimney drain ii) Toe drain iii) Strip drain iv) Relief well v) Horizontal blanket drain vi) Seepage collector and outlet pipes
Geometry of Facility	a) Height b) Volume contained c) Slopes
Stabilization Measures	Define stabilization measures (i.e. berms, soil improvement, shear keys etc.)
Permafrost	a) Yes b) No
Monitoring Program	a) Yes b) No
Closure Plan	a) Plan for tailings (i.e. infilling, dewatering, natural processes, cover, etc.) b) Reclamation surface and cover c) Outlet (Y/N) d) Surface water management
Environmental Factors	a) Determine site climate (consider climate change) b) Precipitation and earthquake events c) Other
Surrounding Areas	Describe upstream and downstream surroundings

Figure 3-4 System definition of tailings dams according to G-FMEA (Schafer et al 2021.)

The block diagram is a graphical representation that provides a functional view of a system and de- aggregates it into functional subsystems. For example, the main system is a dam body and its subsystems are the foundation and drains. The drains can also have multiple levels, as well as outtakes and ditches. Each system or subsystem should be mentioned with its function according to the time frame the risk assessment conducting in. The block diagram improves the understanding of the dam and its components. Figure 3- 5 shows the block diagram adopted in the G-FMEA.

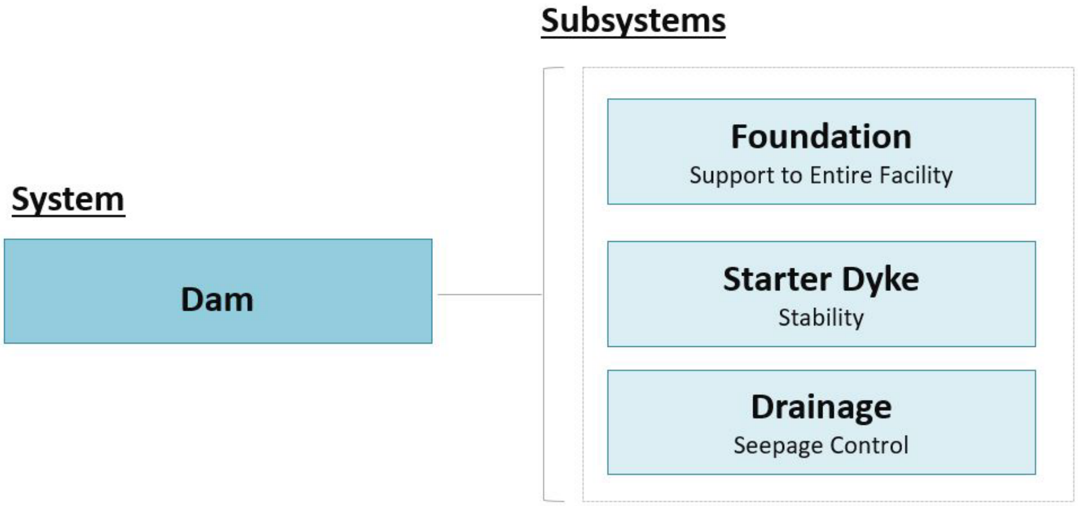


Figure 3- 5: Block diagram in the G-FMEA

The next step is to organize the key element table. The key elements table include the system and subsystems, defining the function of each before and after closure and describing the potential way of failure. The failure of a particular element is defined according to the G-FMEA if the hazard leads to one or both of the following:

- Ultimate failure: the collapse of a tailings dam leading to catastrophic failure results in material disruption to human, environmental, community and post mining land use.
- Serviceability failure: failure of the element to perform the intended function

Table 3-7 shows the key elements table with an example of an element: the foundation.

Table 3-7: Key element table template in the G-FMEA using the foundation as an example of an element.

System	Element	Function (before closure)	Function (after closure)	Failure Description
Dam	1.Foundation	Supports capacity of the dam	Supports capacity of the dam	Instability associated with movements of the soil mass

3.2.2. Level 2: Applicable Failure Modes

The next level of conducting the G-FMEA is to identify all potential failure modes for each key element using the G-FMEA charts. The G-FMEA charts consist of four tables that present extensive and reasonably comprehensive lists of possible failure modes that could occur for various elements of external tailings facilities.

The G-FMEA charts identify 76 failure modes through four elements: drainage system, foundation, dam body and landform. Figure 3-6 shows a graphical representation of the possible failure modes through the key elements for the external tailings facilities according to the G-FMEA charts. As an example, the dam body has 15 failure modes in the G-FMEA charts that can be classified in five groups: erosion (five failure modes), liquefaction (four failure modes), shear (four failure modes), deformation (one failure mode) and destruction of vegetation (one failure mode). For example, erosion failure includes:

1. Surface erosion
2. Internal erosion (contact)
3. Internal erosion (suffusion)
4. Internal erosion (concentrated leak)
5. Toe erosion

The complete G-FMEA charts are provided in Appendix A. Generalized FMEA Charts for Various Elements of External Tailings Facilities in Alberta.

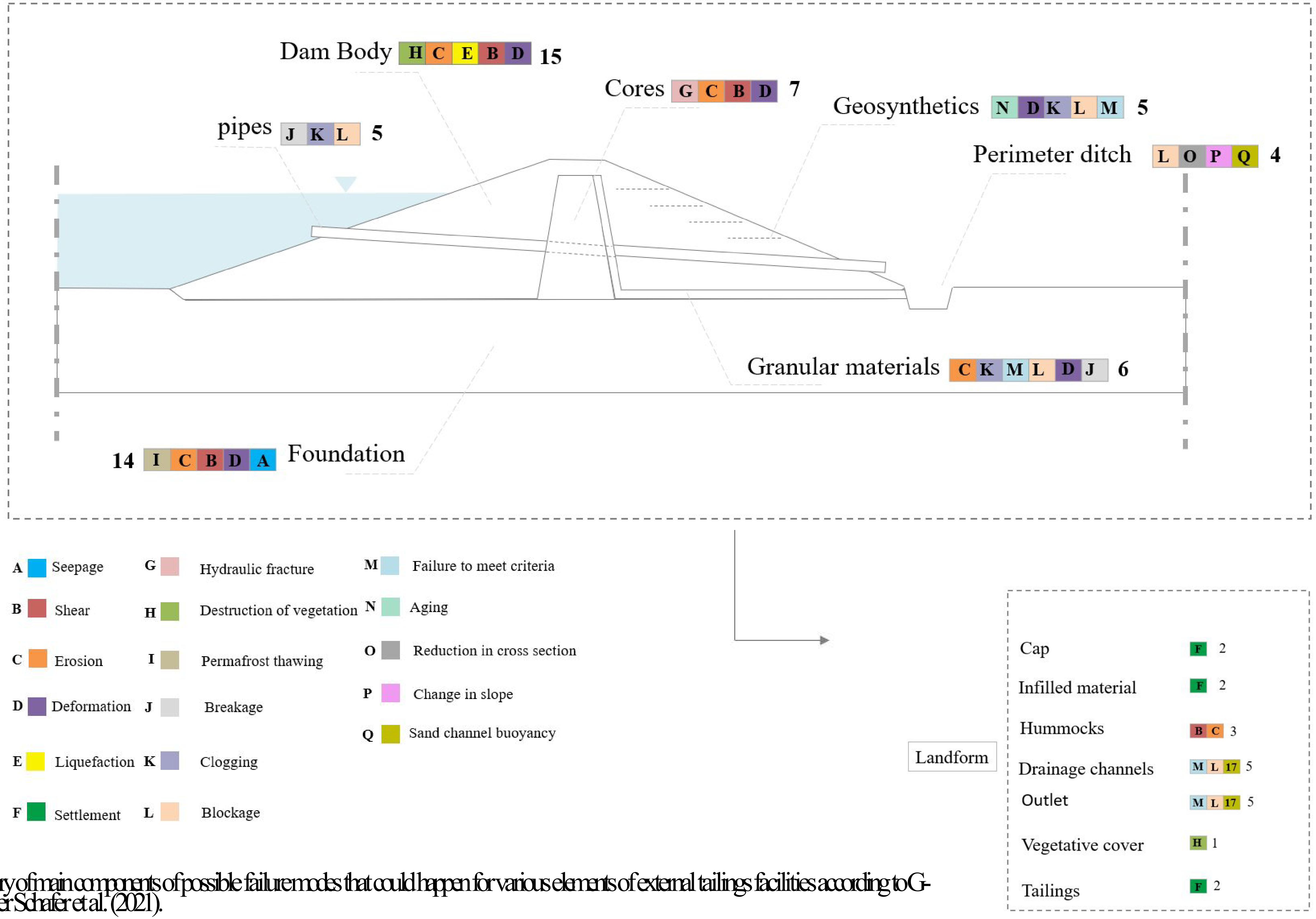


Figure 3-6: Summary of main components of possible failure modes that could happen for various elements of external tailings facilities according to G-FMEA charts. After Schafer et al. (2021).

Each failure mode in the G-FMEA charts is associated with potential triggers, screening assessment of failure modes and failure effects. The screening assessment column asks questions which help to determine the applicability of a failure mode to a specific case study. Also, the screening assessment could be used to outline the information needed to assess the failure mode. An excerpt of the dam body chart is provided in Table 3-9.

Table 3-8: Excerpt from dam body element in G-FMEA chart. (Schafer, et al, 2021.)

ID	Failure mode description	Potential trigger/cause	Screening assessment of failure mode	Failure effects
2	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect, presence of widely gap-graded or non-plastic, gap-graded soils	Is the material widely gap-graded or gap graded non-plastic?	Global instability, seepage on the downstream slope, settlement of the crest, and permeability may increase as erosion progresses or decrease if clogging occurs

Before moving forward in risk assessment, it is necessary to answer this question: how good is our site-specific information? This was assessed by using the developed LOC table to identify the AI and QAI categories, the associated uncertainty degree and confidence level for each applicable failure mode. The outcomes from this step were illustrated in Figure 3-7. This figure consists of AI and QAI categories (vertical axis) for each of the applicable failure modes in the G-FMEA charts (horizontal axis) and for a particular key element. Each value of the AI and QAI was determined using the weight score presented in Table 6 and aligned horizontally to the right with the associated level of confidence and vertically with the detailed contributions of AI and QAI uncertainties. When no AI or QAI category was listed for a particular failure mode, this means that this failure mode is not applicable to the discussed element.

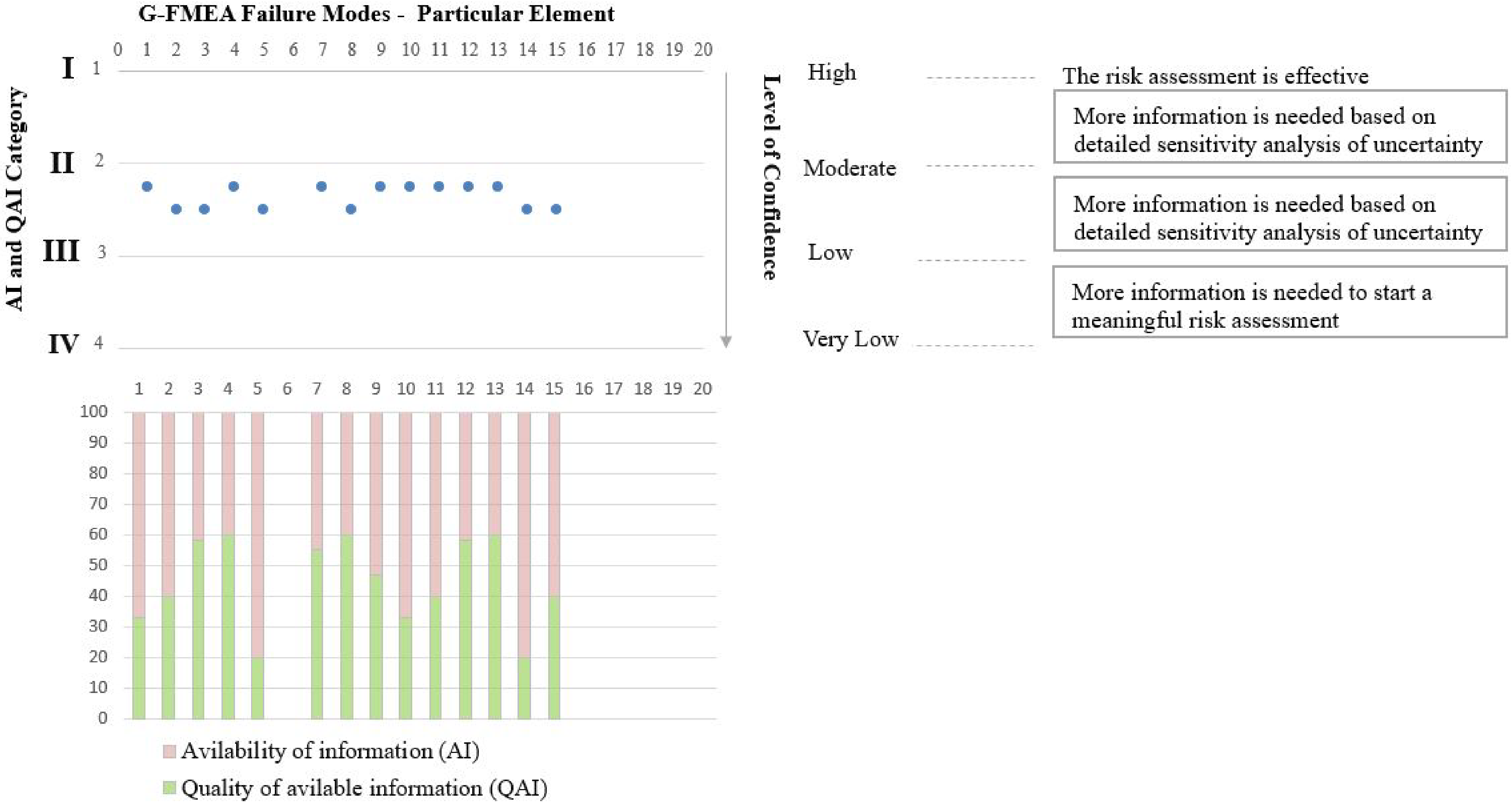


Figure 3-7: AI and QAI categories for the applicable failure modes associated with the level of confidence for particular key element

3.2.3. Level 3: Risk Category

According to the G-FMEA, the risk category for each applicable failure mode is defined using the risk matrix, which consists of two components (likelihood – consequence) applied through different time frames in the closure and post-closure phases. For a specific time frame, the confidence level will be considered along with the risk level. This can be understood as a four-dimensional (4D) risk assessment (likelihood – consequence – confidence – time).

The 4D risk assessment components are:

1. Likelihood

The likelihood rating shown in Table 3-9 has seven categories from "Close to non-credible" to "Almost certain." The likelihood of occurrence is described in terms of the probability of failure and using qualitative descriptors.

Table 3-9: Likelihood rating (Schafer et al., 2021)

Likelihood Rating	**Qualitative Interpretation Guidance**[1]	**Quantitative Interpretation Guidance**	**Annualized Probability of Occurrence**
Almost certain	Almost certain that an incident will occur given the circumstances. Very high probability with one or more occurrences per year.	Greater than a 10% probability in a year	≥0.1
Likely	High likelihood. Commonly observed at similar facilities.	Less than a 10% probability in a year	≥0.01 but <0.1
Possible	Has occurred a number of times within industry and at least once at the site (or at similar facilities in the region).	Greater than a 1% probability in 10 years	≥0.001 but <0.01
Unlikely	Has occurred before within industry, but not at site.	Less than a 1% probability in 10 years	≥0.0001 but <0.001
Rare	Low likelihood of occurrence, but not impossible. Has not occurred at site, but has occurred in industry.	Less than a 1% probability in 100 years	≥0.00001 but <0.0001

Very Rare	Very low likelihood of occurrence, but not impossible. Never heard of in industry, but the possiblity cannot be deemed non-credible.	Less than a 1% probability in 1,000 years	≥0.000001 but <0.00001
Close to non-credible	Extremely remote likelihood of occurrence. Never heard of in industry. Although the mechanisms are technically plausible for the occurrence, it is seen as nearly non-credible.	Less than a 1% probability in 10,000 years	>0.00 but <0.000001

[1] Industry encompasses the mining industry as a whole.

2. Consequence

The consequence rating has five categories that range from "slight" to "severe," as shown in Table 3-10. Those categories classify the degree of the consequence of an element's failure on the rest of the system, the degree of human intervention required, the environmental consequence, the community and post-mining land use.

Table 3-10: Consequence rating. (Schafer et al., 2021)

Consequence Rating[1]	**Consequence of failure of element on the rest of the system**	**Degree of human intervention required**	**Environment**	**Community**	**Post-mining land use**
Slight	Failure of element does not have cascading consequences.	Structural integrity maintained. No intervention or maintenance required.	No movement of tailings beyond the structure footprint.	No impact on local community.	Minimal loss of agreed upon post-mining land use (<5%). The land may be used for a different purpose (i.e., grazing).
Minor	Failure of element has cascading consequences that do not result in global failure.	Structural integrity maintained. Minor or localized intervention or	Released tailings are not toxic,[2] and/or minimal loss of habitat (<5%) of species of special interest,[3] and/or acceptable restoration of water bodies and	Short-term (<5 years) impact[4] to local community. No fatalities.	Moderate loss of agreed-upon post-mining land-use (5-25%), and the land may be used for a different purpose (i.e., grazing) **OR** minimal loss of agreed-upon

		maintenance required.	environment feasible in a short time frame (<5 years).		post-mining land-use (<5%), and the land is sterilized.
Moderate	Failure of element has cascading consequences that do not result in global failure.	Intervention or maintenance required to limit impact of cascading consequences.	Released tailings are not toxic,[2] and/or moderate loss of habitat (5-20%) of species of special interest,[3] and/or acceptable restoration of water bodies and environment feasible in a short time frame (<5 years).	Short-term (<5 years) impact[4] to local community. 1 to 10 fatalities.	Significant loss of agreed-upon post-mining land-use (50-75%), and the land may be used for a different purpose (i.e., grazing) OR moderate loss of agreed-upon post-mining land-use (5-25%), and the land is sterilized.
Major	Global failure of tailings dam with minor release of tailings.	Intervention or maintenance required to maintain function of structure as a whole.	Released tailings are toxic,[2] and/or significant loss of habitat (20-50%) of species of special interest,[3] and/or acceptable restoration of water bodies and environment feasible in a moderate time frame (5-25 years).	Medium-term (5-25 years) impacts[4] to local community. 10 to 100 fatalities.	Significant loss of agreed-upon post-mining land-use (50-75%), and the land is sterilized.
Severe	Global failure of tailings dam with catastrophic release of tailings.	Structural repair not possible.	Released tailings are toxic,[2] and/or very significant loss of habitat (>50%) of species of special interest,[3] and/or acceptable restoration of water bodies and environment unlikely within an extended time frame (>25 years).	Long-term (>25 years) impacts[4] to local community. More than 100 fatalities.	Very significant loss of agreed-upon post-mining land-use (>75%), and the land is sterilized.

Notes:

[1] Assigned consequence should reflect the MOST LIKELY outcome. If assigning consequence with consideration of the worst case or a combination of discrete outcomes, this must be declared.

[2] Toxicity assessment of tailings should consider an assessment of the fluids and solids (leaching potential, acidity, radioactivity).

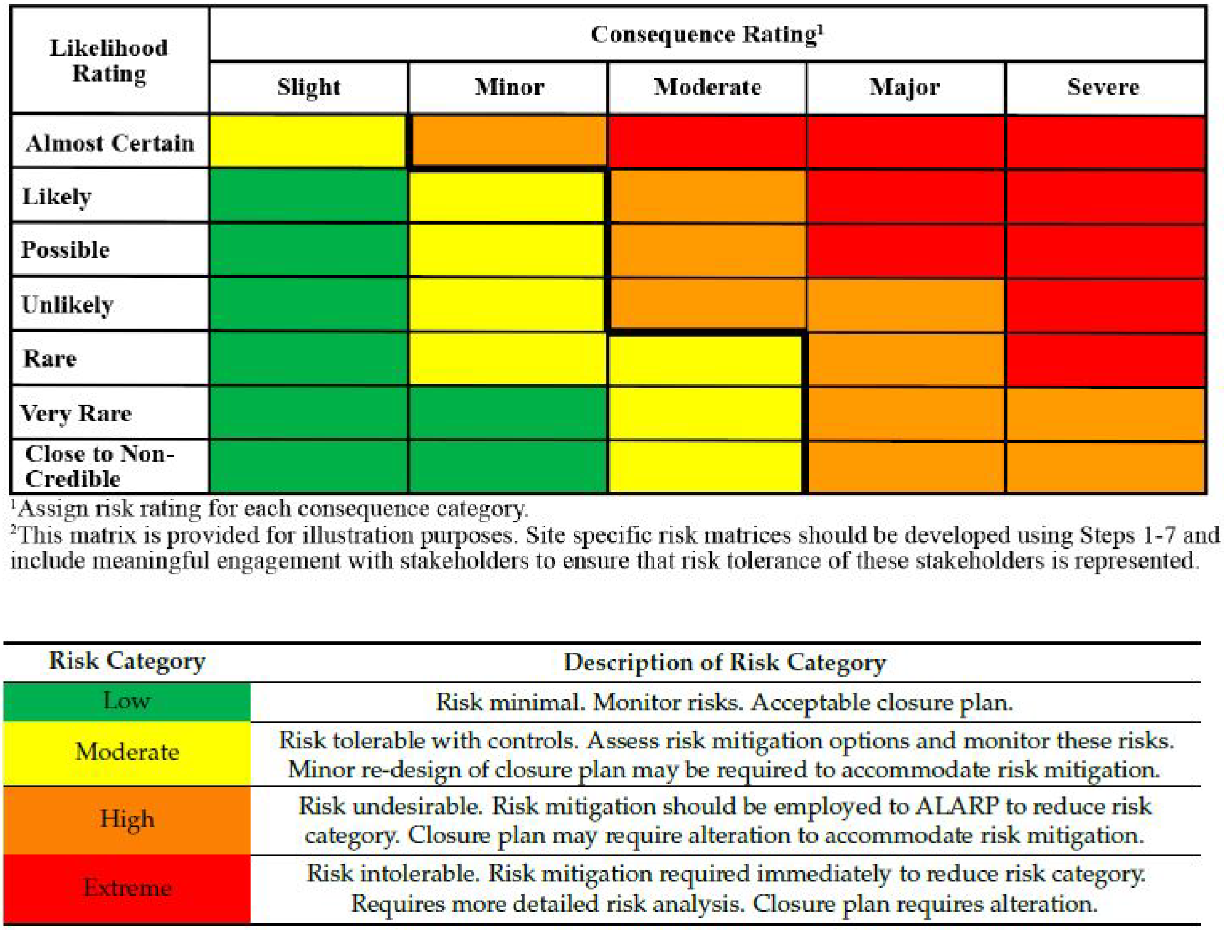
[3] Species of special interest is defined as a species that lives in the inundation area that would be greatly impacted by habitat loss (preferable to select a species that is provincially or federally listed).

[4] Community impacts must be determined through meaningful engagement with stakeholders and may include consideration of health; loss of access or destruction of traditional lands, and housing; destruction of/damage to farmland; harm to livestock; damage to water or soil resources; impacts to trapping and fishing; loss of animals; overall cultural impact, and loss of employment.

[5] Reputation, legal aspects, and economics are not considered in this consequence table as they are considered site- and corporation-specific. It may be necessary to assess these aspects on a site-specific basis.

The seven likelihood ratings and five consequence ratings form the risk matrix. The base-case colour-coded risk matrix in the G-FMEA, shown in Figure 3-8, was adopted in this research. However, the G-FMEA suggests that the colour code should be site-specific and reflect the risk tolerance of all relevant stakeholders (i.e., industry, regulator, the public); and consider technical, social, and economic aspects.

The risk level should be assigned for each consequence category (consequence of failure of element on the rest of the system, degree of human intervention required, environment, community, post-mining land use).



Likelihood Rating	Consequence Rating[1]				
	Slight	Minor	Moderate	Major	Severe
Almost Certain	🟨	🟧	🟥	🟥	🟥
Likely	🟩	🟨	🟧	🟥	🟥
Possible	🟩	🟨	🟧	🟥	🟥
Unlikely	🟩	🟨	🟧	🟧	🟥
Rare	🟩	🟨	🟨	🟧	🟥
Very Rare	🟩	🟩	🟨	🟧	🟧
Close to Non-Credible	🟩	🟩	🟨	🟧	🟧

[1]Assign risk rating for each consequence category.
[2]This matrix is provided for illustration purposes. Site specific risk matrices should be developed using Steps 1-7 and include meaningful engagement with stakeholders to ensure that risk tolerance of these stakeholders is represented.

Risk Category	Description of Risk Category
🟩 Low	Risk minimal. Monitor risks. Acceptable closure plan.
🟨 Moderate	Risk tolerable with controls. Assess risk mitigation options and monitor these risks. Minor re-design of closure plan may be required to accommodate risk mitigation.
🟧 High	Risk undesirable. Risk mitigation should be employed to ALARP to reduce risk category. Closure plan may require alteration to accommodate risk mitigation.
🟥 Extreme	Risk intolerable. Risk mitigation required immediately to reduce risk category. Requires more detailed risk analysis. Closure plan requires alteration.

Figure 3-8: Base-case colour-coded risk matrix in G-FMEA (Schafer et al., 2021).

3. LOC for each applicable failure mode. Determined in Level 2 according to the LOC table and can be read from Figure 3-7.
4. Time: Determine the risk category for each time frame of the closure and post-closure phases (immediate, short, medium, long term).

Table 3-11: Risk rating table for a particular applicable failure mode according to the G-FMEA associated with the level of confidence. After Schafer et al., 2022

Time frame	Likelihood	Consequence				Risk category				Level of confidence				Controls
		Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community	Element failure consequence	Human intervention	Environment	Community	
Immediate term														
Short term														
Medium term														
Long term														

4. Coal Mine Site-Specific Application

The developed level of confidence framework (LOC) was adopted within the generalized FMEA (G-FMEA) risk assessment tool to evaluate a coal mine tailings dam case study in Alberta, Canada. The purpose of this site-specific application is to present a hypothetical scenario on how to implement the LOC framework through the risk assessment process. The LOC framework is expected to help identify and assess how uncertainties regarding the quality of information and its availability (AI, QAI)affect confidence in risk estimation. Further, this case study will highlight the importance of incorporating the time element into the long-term risk assessment of tailings dams, an assessment method which was adopted using the G-FMEA tool. The coal mine site-specific application of the LOC framework followed the levels and steps explained in Figure 3-3. The case study example is based on relevant information extracted from a real mine site and presented in a hypothetical scenario that anonymizes the actual mine site. The level of detailed information provided in this thesis was based on the need to demonstrate the LOC application framework and what was available at the time the research was conducted. Some assumptions were required to illustrate the quantification of the uncertainty rankings. These assumptions do not necessarily reflect the conditions of the actual mine site but are necessary for testing and demonstrating the LOC framework. A summary of the adopted assumptions will be identified through the system definition in Section 4.1.1. The hazards, trigger, failure modes and risks ratings are specific to the hypothetical case and do not reflect actual conditions or level of risk at the site and should not be used for anything beyond the intended purpose of this thesis.

4.1. Level 1 - System Definition- Block Diagram and Key Element

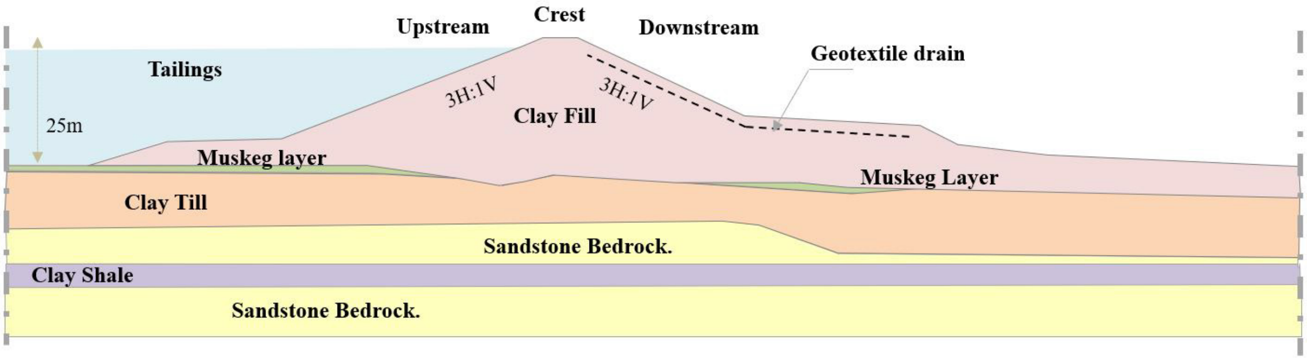
4.1.1. System Definition

The first step in conducting the G-FMEA is to define the system as described in Section 3.2.1. The case study dam is a homogeneous clay dam constructed of overburden (excavated from a local clay till borrow source) and impounds coal tailings and hydrological water. The coal mine tailings mainly consist of fines (saturated sand and fine-grained clay and silt particles). The case study dam was built in one construction phase. The dam is approximately 25 m high, with 3H:1V upstream and downstream slopes and a toe berm on the downstream slope. The toe berm consists of clay fill about 12m high and about 150m out from the toe of the dam. There was no information available at the time of this research about the construction method and deposition used for the dam. The drainage system at the facility consists of a geotextile/gravel drain along the right side of the downstream slope. There are no other drainage systems installed in the left portion of the dam.The dam structure has an emergency spillway and an active pump on the crest.

A section was extracted from the case study and used for subsequent analysis. The foundation of the dam at the analyzed section consists of clay till overlying clay shale and sandstone bedrock. A muskeg layer overlies the clay till and consists of a thin veneer of peat deposits, woody debris, and silt or organic clay.

The analyzed section of the dam consisted of the tallest point near the right abutment of the dam. The section used for analysis was instrumented and monitored on a quarterly basis. A cross-section analyses of the case study is shown in a cross-section analyses of the case study is shown Figure 4-1.

The dam has not received any new tailings for several years, and the facility is proceeding toward closure. The conceptual closure plan aims to divert surface runoff reporting to the facility and lower water levels behind the dam structure through different scenarios of capping strategies and overflow spillways. However, at the time of this research, no detailed information was available for the complete closure plan and the components of the landform design. Identifying uncertainties and risk level at this point-of-closure plan provide risk-based insight for the further detailed design. The available historical climate records include 10 years of monthly mean precipitation and wind speeds from nearby climate stations.



The following assumptions and scenarios were adopted to better show the quantification of the uncertainty rankings at the LOC framework:

- Assumption 1

  Some downstream piezometers were installed originally in the design phase. In this research, we assumed the scenario that these instruments are deteriorating over time which might reflect inaccurate readings in the closure phase. Another scenario that is considered is the possibility that a facility may lack a comprehensive history of piezometric data from its instruments.
- Assumption 2

  The dam fill and foundation for the section presented has a sand zone with no specific parameters available for this layer and no information about its continuity.
- Assumption 3

  Piezometer readings are conducted at different times during the year.
- Assumption 4
- There are shallow depressions on the downstream slope containing standing water with no available records on the historical persistence size and source of the water.
- Assumption 5

  The design stage parameters of the dam material are adopted for stability and seepage assessment through the closure phase, ignoring the dam's evolution over time, such as drain retreat, sand aging, weathering and deterioration of some materials and permeability change
- Assumption 6

  The detailed design memorandum is not available due to Multiple ownerships of the facility mean that only a limited amount of information is transferred and communication gaps occur..
- Assumption 7

  The depth to and characterization of the bedrock are poorly defined, as is whether or not there is a weathered thickness.
- Assumption 8

  The comprehensive historical climate records of the case study are not available.

- Assumption 9

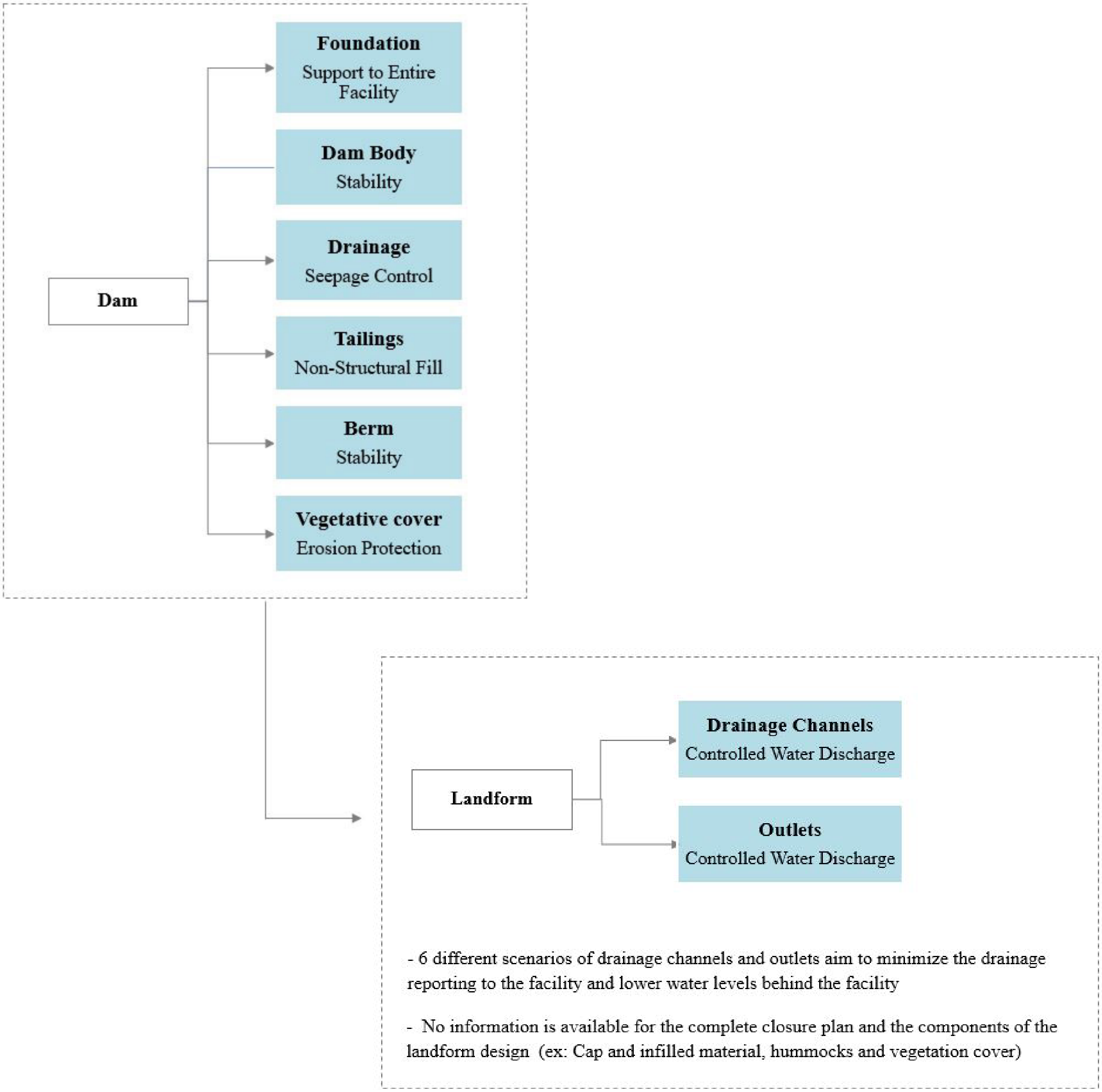
  There is no site-specific information on tailings and the potential for toxicity.
- Assumption 10

  There are no erosion studies for the vegetation and soil at the site.
- Assumption 11

  There is no documentation for the design of the surface water management.

4.1.2. Block Diagram

The next step of conducting the G-FMEA is to develop a block diagram as explained in Section 3.2.1. The block diagram breaks down the system into subsystems and provides information about the function of the components and the relationships between those components.The case study block diagram is shown in Figure 4-2.



- 6 different scenarios of drainage channels and outlets aim to minimize the drainage reporting to the facility and lower water levels behind the facility

- No information is available for the complete closure plan and the components of the landform design (ex: Cap and infilled material, hummocks and vegetation cover)

Figure 4-2: Case study block diagram

4.1.3. Key Elements Table

The key elements table presents descriptions of the system and subsystem elements shown in the block diagram (Table 4-1). This includes the function before and after closure and serviceability failure for each element based on the defined function.

Table 4-1: Case study key elements table

System	Sub-system (Element)	Function before closure	Function after closure	Failure description
Dam	Foundation	Supports the capacity of the dam.	Supports the capacity of the dam.	Instability associated with movements of the soil mass.
	Dam body	Initial containment of tailings. Provides stability.	Provides stability.	Instability
	Drainage	Controls the phreatic surface through the dam.	Controls the phreatic surface through the dam. There is no information on how long the drain will be able to support lowering the phreatic surface over the time of the closure phase. This can be determined by conducting a seepage model incorporating the time element. After some amount of time, the drains will be assumed to fail and will no longer serve a	Drains fail to control phreatic surface.

System	Sub-system (Element)	Function before closure	Function after closure	Failure description
			function in closure. This assumption will be adopted after Schafer et al (2022).	
	Tailings	Non-structural fill	A potential source of instability.	Instability
	Berm	Provides stabilization for the steeper part of downstream slope.	Provides stabilization for the steeper part of downstream slope.	Instability
	Vegetative cover	Stabilization against erosion and protection of the slope.	Stabilization against erosion and protection of the slope.	Fails to provide erosion protection.
Landform	Drainage channels	N/A	Divert surface runoff reports to the facility	Fails to direct flow to the outlet.
	Outlets	N/A	Ensures controlled discharge under exceptional inflow conditions.	Fails to control discharge.

4.2. Level 2 – Applicable Failure Modes and Uncertainty Discussion

In this level, there will be an assessment of how to apply G-FMEA chart failure modes to the case study and also how to apply failure modes to the associated AI and QAI uncertainties

4.2.1. Applicability of Failure Modes

The applicable failure modes for the case study are identified in this section and summarized as colored items in Figure 4-3. The detailed applicable failure modes of the case study are shown in Table 4-2. Most of the G-FMEA failure modes are applicable to the case study based on the screening assessment strategy available in the G-FMEA charts (The complete list of the G-FMEA is available in Appendix A. The screening assessment strategy is part of the G-FMEA charts and consists of the number of questions that could be asked to assess the applicability of each failure mode. The case study coal mine tailings dam has 34 applicable failure modes according to the available information at the time of this research. All failure modes in the G-FMEA chart for the dam body element are applicable, while the foundation element has two inapplicable failure modes. Those are the failure modes posed by the collapse of the karst formation and thawing of the foundation permafrost. As the case study only includes a geotextile drain, the failure modes related to the other kinds of drains (perimeter ditch, granular materials, cores, pipes) are not applicable. No information was available on the detailed closure plan at the time of this research, such as information on a cap design, infilled materials, development of hummocks, details of drainage channels and outlets, and vegetation cover. Consequently, the applicable failure modes of landforms include only those triggered by settlement caused by excessive or differential consolidation of tailings.

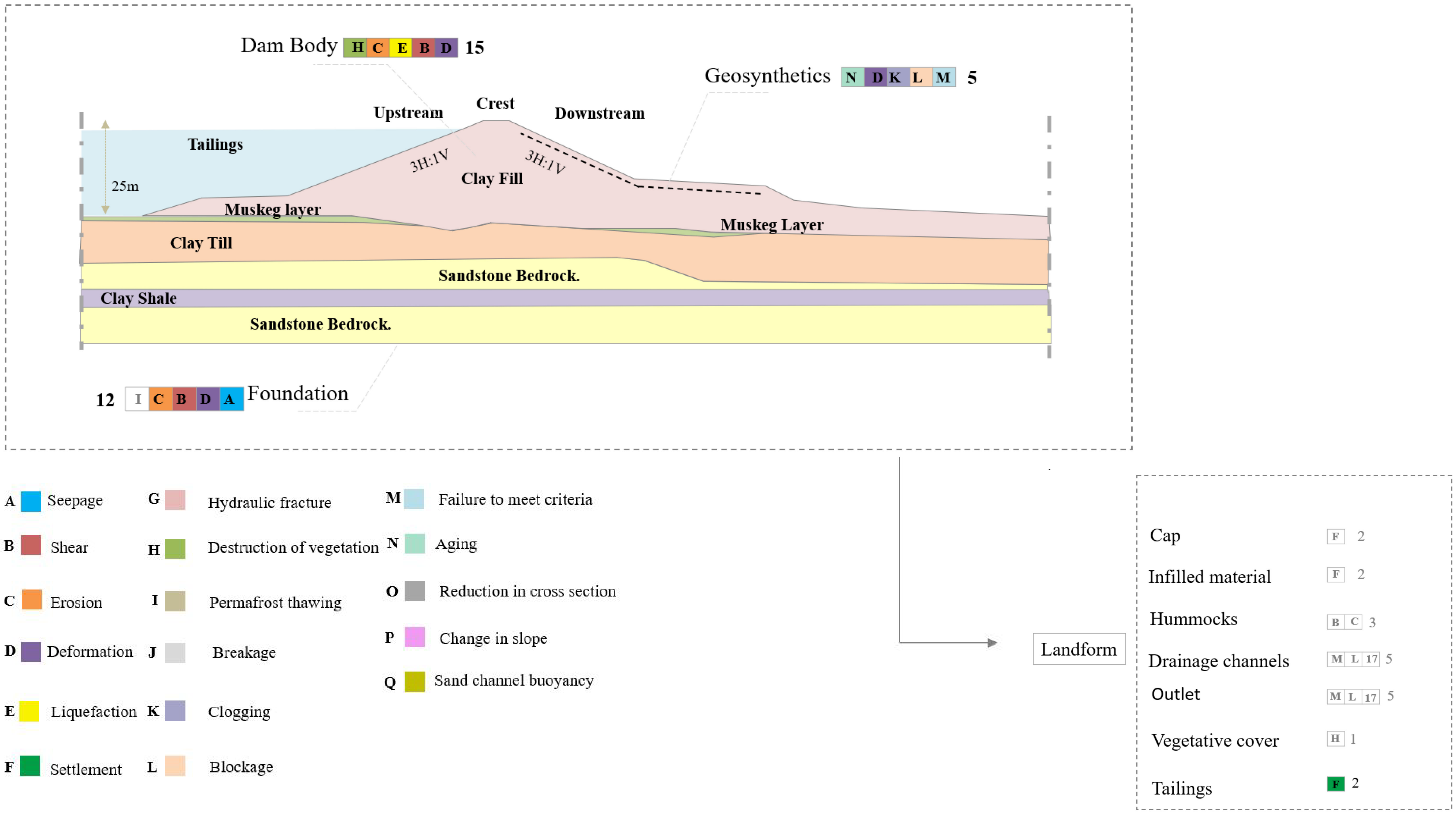


Figure 4-3: The applicable failure modes through the analyzed case study cross section

Table 4-2: The G-FMEA failure modes applicable to the case study of the coal mine tailings dam

Key element	Failure mode group		Failure mode ID in G-FMEA charts
Dam body/Toe berm	H	Destruction of vegetation	1 Destruction of vegetation
	B	Shear	6 Shear failure from changing shear strength 7 Shear failure from changing shear stress
	C	Erosion	2 Internal erosion - suffusion 3 Internal erosion - concentrated leak 4 Internal erosion - contact erosion. 12 Surface erosion from spring sapping 13 Surface erosion from wind and overland flow 14 Toe erosion
	D	Deformation	15 Vertical deformation from consolidation/settlement.
	E	Liquefaction	5 Dynamic liquefaction 8 Static liquefaction from changing mean effective stress 9 Static liquefaction from changing shear stress 10 Static liquefaction from changing shear stress and mean effective stress 11 Static liquefaction from a long-term change in material properties resulting in changing shear strength
Geotextile/gravel drain	N	Aging	16 Aging
	D	Deformation	17 Creep deformation
	K	Clogging	18 Clogging
	L	Blockage	19 Blockage

Key element	Failure mode group		Failure mode ID in G-FMEA charts
	M	Failure to meet criteria	20 Filter cake
Foundation	A	Seepage	1 Heave 4 Excessive/uncontrolled seepage
	D	Deformation	3 Vertical deformation caused by settlement of material
	B	Shear	5 Along pre-existing shear plane from changing shear stress 6 Along new shear plane from changing shear stress 7 Along pre-existing shear plane from changing shear strength 8 Along new shear plane from changing shear strength
	C	Erosion	Internal erosion 9 Contact from global backward erosion 10 Contact from backward erosion piping 11 Contact from contact erosion 12 Contact from suffusion 13 Contact from concentrated leak
Landform	F	Settlement	17 Excessive settlement of tailings 18 Differential settlement of tailings

4.2.2. Uncertainty Discussion

Before moving forward to assess the risk of each applicable failure mode, the uncertainties in the available information and their effects on the confidence of long-term risk estimation need to be discussed. The uncertainties that can affect the confidence of closure risk assessment are discussed in detail below for two failure modes to demonstrate how to implement the LOC framework. Those two failure modes are drain clogging (drain element, ID 18) and surface erosion of the toe berm (dam body element, ID 13). These failure modes were selected as they contain different and important uncertainties, which allow for the illustration of different criteria of the LOC framework. Further, these failure modes illustrate the importance of incorporating the time element through the risk assessment due to the way they may develop over time. Table 4-3 shows the details of the failure modes selected to illustrate the use of the LOC framework.

Table 4-3: G-FMEA failure modes selected for the 4D risk assessment to illustrate the use of the LOC framework excerpted from G-FMEA charts developed by Schafer et al. (2021)

Element	Failure mode identification	Failure mode description	Potential triggers/cause	Screening assessment of failure mode	Failure effects
Geosynthetics/ geotextile/gravel drain	18	Clogging	Biological, chemical, and particulate clogging	Are there dispersive soils present? Are there ferrous soils? Does the permeant contain oily water or sludge? Is there turbid water with high suspended solids? Is there	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface,

				potential for chemical precipitation or biological growth? What is the end land use (e.g., does it involve agriculture or sewage systems that could result in clogging)? Is sediment capable of clogging the drain? What is the grain size distribution?	internal erosion, global instability, the release of water into the downstream shell, erosion on the downstream slope.
Dam body/ Toe berm	13	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion.	Destruction of vegetation, rainfall, melting of snow, wind, increased seepage on the downstream slope from the failure of the drainage	Is the material susceptible to erosion? Is there vegetative cover or erosion protection?	Slope failures (shallow superficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with

			system, increased seepage from internal erosion in embankment.		sediment, development of negative drainage, development of large erosion scarps.

4.2.3. Clogging of the Drain Element

The drainage system at the facility consists of a geotextile/gravel drain placed along the right side of the downstream slope. The function of the drain before and after closure is to control the phreatic surface through the dam fill for the immediate, short, and medium timeframes. There was no available information on the function of the drain in the long-term time frame of the closure phase. However, in this research project, it was assumed that the drain will eventually fail in the long term.

There are five applicable failure modes of geotextile drains according to the G-FMEA charts, as shown in Table 4-2. These include aging, creep deformation, clogging, blockage, and blinding, where fine-grained soils are prevented from entering the geotextile, which creates a filter cake. This section focuses on the uncertainty discussion of the clogging of the drain.

Assessing the drain performance over time is critical for the stability of the structure. If the geotextile drain is considered the main drain in place, its underperformance could lead to an uncontrolled increase in the phreatic surface over time and ultimately impact the stability of the dam. Assessing the drain performance over time requires detailed seepage modeling to identify the drain effectiveness in controlling the phreatic surface during the immediate, short, and medium temporal scales of closure. However, there are different uncertainties in the available information and the assumptions made, which affect the confidence in the seepage model outcomes. The most relevant uncertainties that affect the confidence in the seepage model are discussed below according to the available information and the assumptions adopted in Section 4.1.1.

Assumption 1

Some downstream piezometers were installed originally in the design phase. In this research, we assumed the scenario that these instruments were deteriorating over time which might reflect inaccurate readings in the closure phase. Another scenario considered was the possibility that a facility lacked a comprehensive history of piezometric data from its instruments.

Deterioration of piezometers could include issues such as no gas return, and plugged or damaged parts. Adopting this assumption means that the information obtained from piezometers will contain inaccurate readings, which pose QAI uncertainties. Further, the lack of comprehensive history of data from the piezometric instruments poses AI uncertainties. These readings are critical to predict the behavior of the facility over time regarding failure modes triggered by seepage, such as internal erosion and heave. The readings are also critical for assessing the effectiveness of geotextile drains. Considering Assumption 2 (the dam fill and foundation for the section presented have a sand zone with no specific parameters available for this layer and no information about its continuity), the pore pressure in clay dam fill and the foundation will change slowly, which makes the need for accurate piezometer readings more critical. Using the piezometer readings according to these assumptions could be misleading and result in low confidence in risk assessment outcomes. This uncertainty is related to Criteria 4.6 (status of instruments and risk reduction measures) and classified under Data Category III (Average), high uncertainty and a low confidence level. The design stage piezometers in the downstream area should be assessed to determine whether they need to be replaced.

Further, accurate piezometer readings and a comprehensive history of readings are important to obtain reliable seasonal changes (effect of runoff and infiltration) in the phreatic surface, which is important to predict and assess drain performance over time. This is shown as fluctuations in piezometric readings at the same times for each year. Monitoring these fluctuations by reliable piezometers is important. Considering Assumption 3 (the readings of piezometers are conducted at different times in the year, the seasonal changes of the phreatic surface are not be available). This uncertainty is relevant to Criteria 4.3 (frequency of inspection and time of conducting in the year to obtain the seasonal changes) and classified under Data Category III (average), high uncertainty and a low confidence level.

The assumption of a sandy layer with no specific parameters available about this layer or its continuity was adopted here. Using assumed parameters of this layer based on conceptual geology leads to uncertainty for the seepage analysis outcomes. Considering this assumption in the case study, this issue is classified under Data Category IV (poor), with very high uncertainty and a very low confidence level, assuming that there is no site-specific information on tailings behind the dam and how these changed over time. This uncertainty is classified under Data Category IV (poor), very high uncertainty and a very low confidence level.

Assumption 2

The dam fill and foundation for the section presented have a sand zone with no specific parameters available for this layer and no information about its continuity.

Using assumed parameters of this layer based on conceptual geology leads to uncertainty for the seepage analysis outcomes. Considering this assumption in the case study, this issue is classified under Data Category IV (poor), with very high uncertainty and a very low confidence level.

Assumption 4

There are shallow depressions on the downstream slope containing standing water with no available records on the historical persistence, size and source of the water. Obtaining the record of changes in visual observations during inspections is important as these changes are helpful in several ways: they contribute to increasing our ability to forecast the behavior of the dam body over time and they help in the applicability decisions of some failure modes. Obtaining the records of change for the assumed ponding depressions contributes to increasing our ability to determine the applicability of internal surface erosion and drain performance retreat. The increased wetness in the depression from the surface runoff with some soil particles indicates surface erosion. In cases in which there is seepage from the dam, soil particles suggest internal erosion or drain performance retreat. Further, the frequency of observed depressions affects our ability to identify the likelihood of a failure mode according to the G-FMEA likelihood rating shown in Table 3-9.

This uncertainty is relevant to Criteria 4.4. (level of detail in inspection reports such as seasonal changes and records of changes of visual observations, and documentation meeting the standards for dam and environment safety). It is classified under Data Category III (average), with high uncertainty and low confidence level according to the LOC framework explained in Table 3-3.

Assumption 5

The design stage parameters of the dam material are adopted in stability and seepage assessment through the closure phase, ignoring the dam's evolution over time.

Considering this parameter in the seepage model without formal continuous site investigation ignores the dam evolution over time. This uncertainty is relevant to Criteria 4.1. (conducting investigation and sample tests over time, including physical and chemical field investigation). It is classified under Data Category IV (poor), with very high uncertainty and very low confidence level according to the LOC framework explained in Table 3-3.

Assumption 6

The detailed design memorandum is not available due to an ineffective management transfer plan and a gap in communication when the ownership of the facility changes.

This uncertainty is relevant to Criteria 4.10 (data management through the transferring of the facility ownership and risk communication between stakeholders). It is classified under Data Category III (average), with high uncertainty and a low confidence level.

Assumption 7

The depth where the bedrock starts, characterization of the bedrock, and if there is a weathered thickness are poorly defined.

Critical for conducting the seepage model within the dam are detailed defined information about foundation components and at what elevation under the dam the fill starts. This uncertainty issue is classified under Data Category III (verage), with high uncertainty and a low confidence level.

Assumption 9

There is no site-specific information on tailings and the potential for toxicity.

This uncertainty is classified under Data Category IV (poor), with very high uncertainty and a very low confidence level.

According to the LOC failure mode base application, the data category for the clogging of drain failure mode is 3.3 and is assigned as Data Category III with a low level of confidence according to the available information and assumed scenarios. Table 4-4 shows the detailed calculation of the clogging-of-drain-failure mode. The failure mode is assessed over four phases: design, construction, operation, and closure. The criteria for each phase are assigned based on the most relevant. For the design phase, all the criteria are considered and assigned as Data Category III (score weighting 0.45) for Criteria 1.1 (level of field investigation) and 1.2 (testing). The data category for Criteria 1.3 (documentation) is assigned as IV (weighting score 0.6). For the construction phase, the four criteria are considered relevant and assigned as Data Category IV (weighting score of construction phase 0.6 divided by the four criteria is equal to 0.15). The operation phase has seven relevant criteria and is assigned as Data Category III (weighting score of operation phase 0.45 divided by the seven criteria is equal to 0.6). The closure phase has 10 criteria. For this failure mode, Criteria 4.2 (climate records) and 4.5 (maintenance and repairs) are not considered the most relevant criteria. Consequently, the weighting score for the rest of the criteria is considered as the score of the closure phase divided by eight. For example, for Criteria 4.1 (conducting investigation and sample tests over time including physical and chemical field investigation), the assigned data category is IV (weighting score of closure phase is one divided by eight and equal to 0.6). The total data category of the failure mode is the sum of all criteria.

Table 4-4: LOC failure mode base application - clogging of geotextile drain

Criteria	**Category I**	**Category II**	**Category III**	**Category IV**
1. Design				
1.1. Level of field investigation			0.45	
1.2. Testing used to estimate the parameters			0.45	
1.3. Documentation				0.60
2. Construction				
2.1. As-built record				0.15
2.2. QA/QC program				0.15
2.3. Supervision of EOR				0.15
2.4. IRB				0.15
3. Operation				
3.1. Continues field measurement			0.06	
3.2. Water management level in operation			0.06	
3.3. Operation, maintenance and surveillance manual (OMS)			0.06	
3.4. Frequency and date of inspection(s) during the year to account for seasonal changes			0.06	
3.5. 3.5. Level of detail in inspection report such as seasonal changes and records of changes of visual observations			0.06	
3.6. EOR			0.06	
3.7. IRB			0.06	
4. Closure phase				

4.1. Conducting investigation and sample tests over time including physical and chemical field investigations				0.13
4.2. Climate change records				
4.3. Frequency and date of inspection(s) during the year to account for seasonal changes.			0.09	
4.4. Level of detail in inspection report such as seasonal changes and records of changes of visual observations. Documentation meeting the standards for dam and environment safety.			0.09	
4.5. Maintenance and repairs				
4.6. Status of instruments and risk reduction measures			0.09	
4.7. QA/QC			0.09	
4.8. EOR			0.09	
4.9. IRB			0.09	
4.10. Data management by transferring facility ownership and risk communication between stakeholders.			0.09	
SUM	0	0	2.1	1.325
Failure mode data category	**3.3**			

4.2.4. Surface Erosion of the Downstream Slope Toe Berm

The function of the design of the toe berm before and after closure is to maintain adequate stability to the downstream slope. The downstream slope and the toe berm are well-vegetated. The toe berm has 15 applicable failure modes, as shown in Table 4-2 This section will focus on the surface erosion failure mode triggered by overland flow to illustrate another example of the implementation of the failure mode base application of the LOC framework.

Surface erosion results in gullies and stable rills, which are usually repaired once erosion appears by being re-filled with compacted clay. The surface of the clay fill is exposed to weathering conditions, making the surface erosion failure mode applicable to the dam case study. Erosion could result in failure in the function design of the dam fill and toe berm: failure to retain tailings (Slingerland et al., 2018 and 2019). Erosion gullies are considered to be less critical in the immediate and short term as there is still an opportunity for maintenance (Schafer et al., 2022). However, medium- and long-term risk assessments for surface erosion are critical after decommissioning the facility. The most relevant uncertainties that affect confidence in long-term surface erosion assessments are discussed below, according to the available information and the assumptions adopted in Section 4.1.1.

<u>Assumption 8</u>

The comprehensive historical climate records of the case study are not available.

Climate change critera is significant criteria in that it defines the potential medium- and long-term risks for surface erosion (Slingerland, 2019). Uncertainties in the available information of this criteria can highly affect confidence in the medium- and long-term risk assessments of surface erosion.

Predicted changes in intensity and frequency of precipitation, evaporation, soil moisture, intensity duration frequency (IDF), vegetation type, and snow depth significantly influence the long-term assessment of risk induced by erosion (Slingerland, 2019). These changes are usually assessed through a climate change model. The available historical climate records are critical for the ability to build a long-term climate change model. Considering Assumption 8 (the comprehensive historical climate records of the case study are not available), there is a gap in our ability to project climate data for mine sites. The available climate data for the case study consists of 10 years of historical precipitation and wind speed from regional stations and a monthly mean. This is not enough to predict a long-term time frame for climate change, which is assumed to extend 1000 years. The sub-daily climate information, such as precipitation records from the smallest possible radius around the site, is recommended for conducting effective long-term landscape evolution (Paul et al., 2021). Further, regarding the global climate change records limitations, climate change models are reliable until the year 2100 based on Alberta available climate data, which is also less than the aimed-for long-term time frame (1000 years) (Schafer, 2022). Predictions of climate change to 2500 years are available but with a high level of uncertainty (Schafer 2022). The short historical climate record available for the case study and the reliability of climate change models beyond 2100 in Alberta introduce high uncertainty in the long-term risk assessment of the dam case study in the failure modes triggered by climate change, such as surface erosion. This uncertainty issue is relevant to Criteria 4. 2 (the climate change records) and is classified under Data Category IV (poor), with very high uncertainty and very low confidence.

Assumption 9

(There is no site-specific information about tailings and the potential for toxicity.) Assuming that there is no site-specific information about tailings and the potential for toxicity, the instability posed by surface erosion will have higher consequences. This uncertainty issue is classified under Data Category IV (poor), with very high uncertainty and a very low confidence level, according to Table 3-3.

Assumption 4

There are depressions with ponding water in the downstream slope with no record of changes on how the nature of this ponding water and dimensions of depressions are changed over time. These changes contribute to increasing our ability to more reliably predict erosion. This uncertainty issue is classified under Data Category III (average), with high uncertainty and a low confidence level, according to Table 3-3.

The assumptions were made as part of the thesis research and may not reflect the actual site condition. Table 4-5 shows the detailed calculation of the surface erosion failure mode. The available information and assumed scenarios were assessed through all different phases: design, construction, operation, and closure. All the criteria for each phase are assigned as relevant for this failure mode. For the design phase, each criteria is assigned as Data Category IV (score weighting 0.6) as it is assumed that there are no erosion studies for the vegetation and soil at the site and there is no documentation for the design of the surface water management.

For the construction phase, the four criteria are considered relevant and assigned as Data Category IV (weighting score of construction phase 0.6 divided by four criteria is equal to 0.15).

The operation phase has seven relevant criteria and is assigned as Data Category III (weighting score of operation phase 0.45 divided by the seven criteria is equal to 0.6).

All the closure phase criteria are relevant and scored differently. As an example, for criteria 4.2 (climate records), the assigned data category is IV (weighting score of closure phase is one divided by 10 criteria and is equal to 0.1).

The total data category of the failure mode is the sum of all criteria and is equal to 3.7. This reflects a high level of uncertainty and low confidence in the risk assessment outcomes of this failure mode based on the available information and assumed scenarios.

Table 4-5: LOC application of surface erosion failure mode.

Criteria	Category I	Category II	Category III	Category IV
1. Design				
1.1. Level of field investigation				0.60
1.2. Testing used to estimate the parameters				0.60
1.3. Documentation				0.60
2. Construction				

2.1. As-built record				0.15
2.2. QA/QC program				0.15
2.3. Supervision of EOR				0.15
2.4. IRB				0.15
3. Operation				
3.1. Continues field measurement			0.06	
3.2. Water management level in operation			0.06	
3.3 OMS			0.06	
3.4. Frequency and date of inspection(s) during the year to account for seasonal changes.			0.06	
3.5. 3.5. Level of detail in inspection report such as seasonal changes and records of changes of visual observations.			0.06	
3.6. EOR			0.06	
3.7. IRB			0.06	
4. Closure phase				
4.1. Conducting investigation and sample tests over time including physical and chemical field investigations				0.10
4.2. Climate change records				0.10
4.3. Frequency and date of inspection(s) during the year to account for seasonal changes.			0.08	
4.4. Level of detail in inspection report such as seasonal changes and records of changes of visual			0.08	

observations. Documentation meeting the standards for dam and environment safety.				
4.5. Maintenance and repairs			0.08	
4.6. Status of instruments and risk reduction measures			0.08	
4.7. QA/QC			0.08	
4.8. EOR			0.08	
4.9. IRB			0.08	
4.10. Data management through transferring facility ownership and risk communication between stakeholders.			0.08	
SUM	0	0	1.05	2.60
Failure mode data category	**3.7**			

The complete LOC application for all applicable failure modes of the presented section is shown in Figure 4-4. Different confidence levels are shown for the same failure modes alongside the different key elements. The site-specific coal mine application of the LOC framework shows that the majority of applicable failure modes will have low to very low confidence levels according to the current status of available information and the assumed scenarios discussed above.

The next step is to incorporate the confidence level for each applicable failure mode into identification of the risk category using the likelihood and consequence rating according to G-FMEA for each time frame through the closure phase (immediate, short, medium, and long term). This step will demonstrate the potential change in the risk category through different time frames and how much this risk category reflects the real case considering the confidence status. This will be referred to as the 4D risk category (likelihood, consequence, confidence, time).

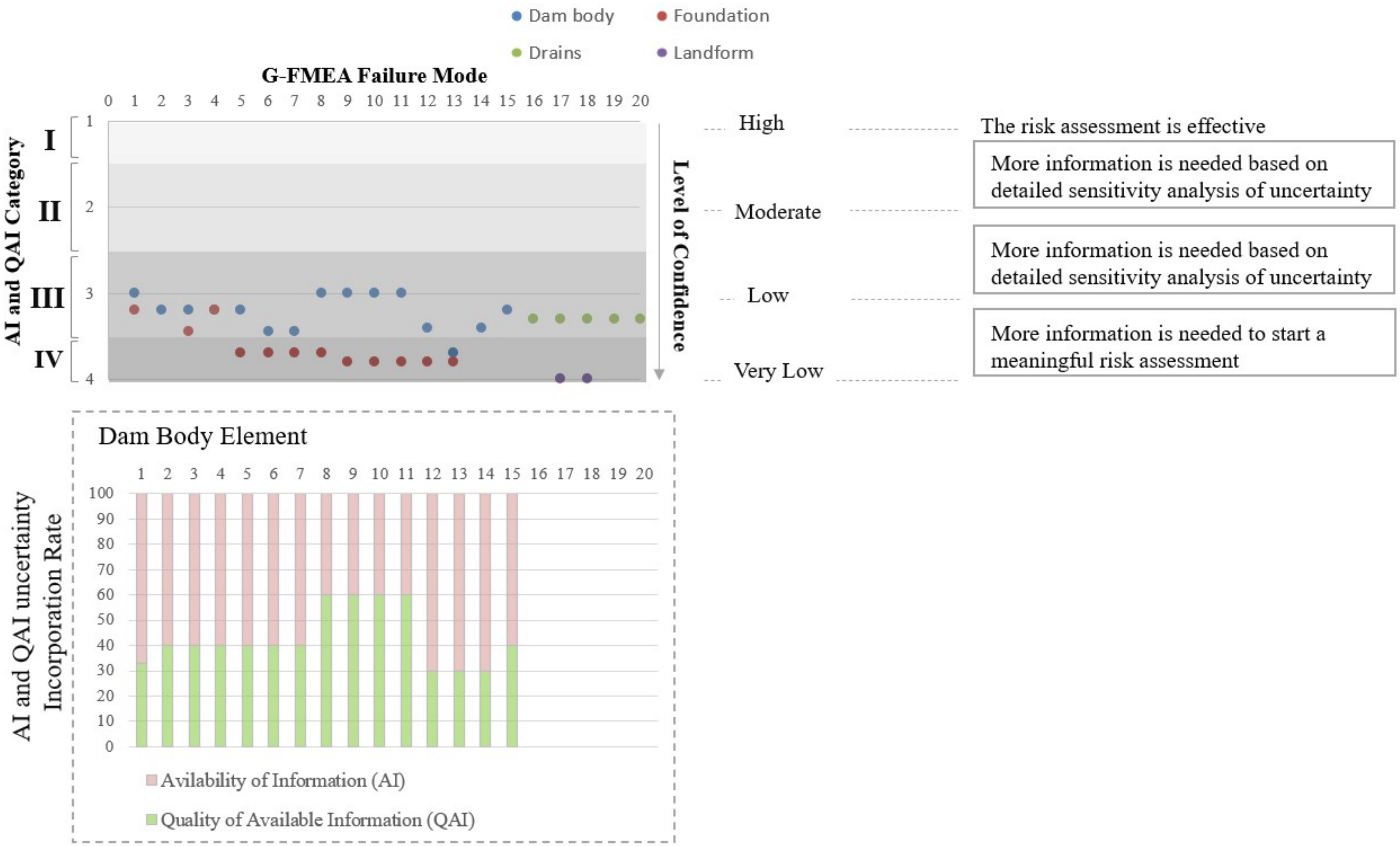


Figure 4-4: Case study for LOC application

4.3. Level 3 – 4D Risk Category (likelihood, consequence, confidence, time)

In this level, the 4D risk category is assigned with a detailed description for the failure modes for clogging the geotextile drain and surface erosion.

4.3.1. Clogging the Drain Element

The risk category for the clogging failure mode over time was assigned considering the uncertainties posed by the assumed scenarios. The G-FMEA likelihood and consequence rating reviewed in Section 3.2 was adopted. As recommended in the G-FMEA, the risk assessment should take place over the four temporal scales: immediate-term, short-term, medium-term, and long-term.

It is expected that the immediate-term and short-term for the case study facility will fall within the adaptive management period, when the facility may be at its greatest risk of failure before reaching equilibrium and the operator will have the greatest capacity to respond. The medium-term period will fall within the reactive management, where the monitoring may occur on a reaction basis once the trigger events occur, and the long-term, up to 1000 years. For this research, it is assumed that the geotextile drain will control the phreatic surface for the immediate-term, short-term, and medium-term periods. As such, serviceability failure occurs when the drain is no longer able to control the phreatic surface. For the long-term, the drains were assumed to fail, and so the long-term risk assessment was not conducted for this failure mode. The risk assessments for the immediate-term, short-term, and medium-term for the clogging-of-the-drain failure mode are provided in Table 4-6.

As time progresses, there is an increase in the likelihood of the drain failing due to clogging from "possible"? in the immediate- and short-term to "likely" in the medium-term. The consequences also increase over time. Because drainage reporting to the facility at the time of closure was minimized, it is expected that the failure of the geotextile drain may result in a minor rise in the phreatic surface in the immediate- and short-term. Using this assumption, a minor consequence rating will be adopted with no expectation of global failure. This is coupled with slight human intervention due to the minimum presence of staff on site, as the mine site will stop operatingfollowing closure. There are also slight environmental and community consequences as there is no global failure expected. However, this required a seepage model to identify the effectiveness of drainage procedures, which is associated with the uncertainties discussed before and poses low confidence in the seepage model outcomes.

For the medium-term, if the facility requires this drain for stability and considering the scenario of having a sand zone within the dam fill and foundation, it is expected that failure of the drain could result in a rise in the phreatic surface, resulting in an increase in seepage and the formation of a wet zone on the reclamation surface. This required supported modeling and onsite monitoring. Using this assumption results in an increased consequence rating, assigned as moderate. This consequence may require human intervention and maintenance, resulting in a moderate consequence rating of human intervention. As no global failure is expected and no tailings are expected to move beyond the facility, a slight consequence rating was assigned to the environment. It is expected that there may be a medium-term impact on the local community if a wet zone forms on the reclamation surface, depending on the end-land use. This impact was assigned as   a minor consequence rating.

As shown in Table 4-6, the risk ratings increase as time progresses for element failure, human intervention, and community. The environmental risk rating remains low through the immediate-, short-, and medium-terms as global failure is not expected, and tailings are not expected to go beyond the dam downstream due to a failure of the geotextile drain.

As the confidence in the required supported seepage model outcomes is low due to the presented uncertaities, the risk category assigned in the immediate- and short-terms may not be reliable. The real risk rating might be lower or higher if more information is available, reducing AI and QAI uncertainties. Reducing uncertainties by having more information does not always necessarily mean a safer case. If we get more information and reduce the AI and QAI uncertainties, this extra information could have some critical implications, leading us to increase the risk level. Apopting Assumption 2 (there is a sand zone through the dam fill with some details of information and assumed parameters), we assigned a medium risk level to element failure as we were not very sure about how critical the zone was. If more investigations are conducted and we have more information on the continuity and exact properties of the sand zone, and they are assessed as critical, the risk rating level will be considered high instead of medium in the immediate and short term for the “element failure” criteria due to the presence of critical sand zone through the dam. The other risk ratings in the matrix are subject to be higher as well in case more information is formed that the sand zone is critical. The potential real risk categories in cases of fewer uncertainties and more information regarding the sand zone are provided in Table 4-6.

Table 4-6: 4D Risk assessment for failure mode for clogging of geotextile drain.

Temporal Scale	Likelihood	Consequence				Risk rating				
		Element failure	Human intervention	Environment	community	Element failure	Human intervention	Environment	community	Confidence
Immediate - term	Possible	Minor	Slight	Slight	Slight	M	L	L	L	L
Short-term	Possible	Minor	Slight	Slight	Slight	M	L	L	L	L
Medium-term	Likely	Moderate	Minor	Slight	Minor	H	M	L	M	L

A potential real case of risk rating after reducing the AI and QAI uncertainties.

↓

H	M	M	M
H	M	M	M
S	H	M	H

4.3.2. Surface Erosion of the Downstream Slope and Toe Berm

The risk category of surface erosion failure mode over time will be assigned considering the uncertainties and the assumed scenarios discussed in Section 4.2.4. The G-FMEA likelihood and consequence rating reviewed in Section 3.2 will be adopted. The risk assessments for the immediate-term, short-term, medium-term, and long-term for surface erosion are provided in Table 4-7.

As the gullies are assumed to be already in the site according to the assumed scenarios in Section 4.2.3, it is expected that surface erosion will occur with a "possible" likelihood in the immediate- and short-term. Erosion gullies are considered to be less critical in the immediate- and short-term as there is still an opportunity for maintenance (Schafer et al., 2022). Assuming that the maintenance is available in those terms, it is expected to have a minor consequence rating for element failure, human intervention, environment, and slightly for the community.

The risk level of erosion failure mode is expected to be greater due to climate change effects. Moving forward to medium- and long-term temporal scales, it is expected that the likelihood of the surface erosion failure mode will change from possible to likely due to climate change and the destruction of vegetation.

Table 4-7 shows an increase in the risk rating as time progresses for different consequence categories. For the immediate- and short-terms, a minor consequence of element failure was assigned, resulting in a medium risk rating. For human intervention, there was an increase from a minor consequence rating in the immediate- and short-terms to moderate for the medium-term and long-term. As the likelihood of surface erosion may be greater here, there is a need for ongoing maintenance of the dam surface, which results in a higher consequence for human intervention. The environmental consequence was assigned minor for the immediate- and short-terms and is expected to increase to moderate for the medium- and long-terms.

Regarding the community consequence, the risk rating increases from slight (the gullies will have ongoing repair) in the immediate-term and short-term to minor in the medium-term and long-term as the employees may be present on site.

However, due to the uncertainties associated with the medium- and long-terms, the risk rating may be higher. As an example, if more information is available on the wind and overland flow and is assessed to be serious triggers for surface erosion, the likelihood of surface erosion will increase and poses a high level of risk instead of medium in the immediate and short term for the "element failure" criteria. The other risk ratings in the matrix are subject to be higher as well. Table 4-7 provides the potential real risk categories in the case of having more information of wind and overland.

Table 4-7: 4D Risk assessment of surface erosion failure mode: toe berm element

Temporal scale	Likelihood	Consequence				Risk rating				
		Element failure	Human intervention	Environment	community	Element failure	Human intervention	Environment	community	Confidence
Immediate term	Possible	Minor	Minor	Minor	Slight	M	M	M	L	L
Short term	Possible	Minor	Minor	Minor	Slight	M	M	M	L	L
Medium term	Likely	Moderate	Moderate	Moderate	Minor	H	H	H	M	L
Long term	Likely	Moderate	Moderate	Moderate	Minor	H	H	H	M	L

A potential real case of risk rating after reducing the AI and QAI uncertainties.

H	H	H	M
H	H	H	M
S	S	S	H
S	S	S	H

5. Conclusions and Future Work

Assessing the risk associated with the long-term behavior of tailings dams is critical for achieving a safe closure plan for these facilities. The risk-based closure plan provides the opportunity to define and assess potential public and environmental post-closure risks so that they can be considered throughout the design of the closure. Site-specific information about tailings dams is critical for conducting a risk-based closure plan. This information typically includes site data, design details, construction materials, construction methods, past behavior of the structure, historical climate data, etc.

Conducting a risk-based closure plan is a challenge in industries with limited information because uncertainties diminish confidence in risk-assessment outcomes. This research focused on the epistemic uncertainties (insufficient knowledge) which could be related to the availability of information and its quality. Uncertainties could be caused by missing, incomplete, or outdated information, the term for which is available information (AI) uncertainties. The other kind of uncertainties discussed in this research could result from geotechnical assumptions or methods used in site investigation, analysis, and design. The term for these uncertainties is quality of available information (QAI). A risk assessment conducted without considering the level of uncertainty in AI and QAI could be misleading in the design of closure. The confidence in long-term risk assessment outcomes may be impacted by additional information uncertainties related to the lack of understanding of the aging process of a facility after its closure and the difficulty in predicting external loads. However, these uncertainties will not be addressed in this research.

Using industry experience and the most recent relevant literature, the research in this thesis summarized eight main sources of uncertainties regarding information that stakeholders are likely to encounter and which can compromise a reliable risk assessment, shown in Figure 2-5. A Level of Confidence (LOC) framework was developed to incorporate these uncertainties throughout the risk assessment. The LOC tool can be used to assess confidence in risk assessment outcomes through all life cycles of tailings dams, which allows a meaningful change to be made to reduce the long-term cumulative effects of uncertainties. However, in many cases, this is not possible, as in the case of legacy tailings facilities in need of closure. While this confidence tool was developed with coal mine tailings dams in Alberta in mind, it could be easily adapted to other types of mines and locations.

The LOC framework provides a systematic method for assessing confidence in risk assessment outcomes in a comprehensive but simple manner that can be readily applied by the practitioner. The LOC framework requires that site-specific information about the facility be broken down into four categories according to the developed descriptive categorization regarding AI and QAI uncertainties. These data categories were translated into confidence levels in the estimated risk. The confidence levels have a score of high, medium, low, and very low. The LOC tool was developed to be used in conjunction with the generalized FMEA (G-FMEA) as the risk assessment tool.

The LOC tool can be used to assess the data category and the level of uncertainty for the whole structure and can be applied on a failure mode basis. Guidelines were provided on how to calculate the data category and confidence level for the LOC failure mode basis application. The LOC failure mode basis application suggested considering the criteria most relevant to the failure mode.

The second part of this research demonstrated how the LOC framework can be applied to a case study site. The case study site used for this work is an external tailings facility located at a coal mine site in western Alberta. For the coal mine facility, the system definition and block diagram were developed and used to develop failures modes for the individual dam element using the generalized charts from the G-FMEA. From here, selected failure modes (clogging of drains and surface erosion of the berm) were used to provide a detailed explanation about how the LOC framework can be used to assign the data categories of the available information. Some assumptions were made to augment the available information to better show the quantification of the uncertainty rankings. These assumptions do not necessarily reflect the conditions of the case study adopted but were necessary for testing the LOC framework. The failure modes were assessed through the different time frames showing how the risk level could change over time and was associated with the confidence level based on the assigned data category. A potential scenario of the risk matrix was discussed, considering the confidence assigned to each failure mode. In both selected failure modes, the risk rating increased as the time frame increased and had high uncertainty based on the available information and the assumptions.. The drain clogging failure mode had high uncertainty posed mainly by the assumption of the not well-defined parameters of the material within the dam, while the surface erosion had a high uncertainty mainly from the assumption of pore climate data available.

The LOC application was conducted for all the applicable failure modes in the analyzed cross section. The majority of the applicable failure modes had low to very low confidence according to the current status of available information and the assumptions.. According to the assigned uncertainties issues based on the available information and the assumptions, many identified risks could have a higher ranking while other unknown risks could not be considered.

Therefore more detailed information is required at the site in order to undertake the design of a risk-informed closure plan.

The future work of developing the LOC framework is to define where the operators and/or regulators need to reduce the uncertainties to upgrade confidence in risk assessment outcomes by developing an information-gathering strategy. This should be accompanied by research on how to prioritize which failure modes and related uncertainties are targeted during the information-gathering strategy to maximize the use of resources and impact. Further development of the LOC framework could also explore how to include various stakeholder groups throughout the entire risk assessment process including risk evaluation/communication/monitoring as an alternative to Figure 2-2. The limitations of the LOC framework lie in considering the confidence level out of the risk matrix. While this research presents a 4D risk assessment (likelihood, consequence, confidence, time), the risk ranking is still assessed by the two-dimensional risk matrix (likelihood, consequence). The current challenge is to expand the risk matrix to include the confidence dimension. The current LOC framework can be used as a basis for future work of the likelihood-consequence-confidence risk rating. The descriptive data categories for the closure phase in the LOC framework can be the foundation on which to develop design acceptance criteria for the closure plan where the best state of the information and methods need to be followed. The design acceptance criteria can be established using the characteristics of Category I in the LOC table. As the probabilistic approaches can not capture well uncertainty posed by poor knowledge, another area of future work is to explore how to improve and incorporate probabilistic approaches for epistemic uncertainty.

6. References.

Armen Der Kiureghian et Ove Ditlevsen. 2009. Aleatory or epistemic? does it matter? Structural Safety, 31(2):105–112.

Ballard, J.C., Vanden Berghe, J.F., Jewell, R. and Pirson, M. 2008. Some lessons from a recent tailings dam failure. Proceeding of the Fourth International Conference on Forensic Engineering, Institution of Civil Engineers, London, UK.

Berghe J.F.V., Ballard, J.C., Pirson, M. and Reh, U. 2011. Risks of Tailings Dams Failure. Geotechnical Safety and Risk ISGSR, 209(2010), pp. 209–216. Available at: https://hdl.handle.net/20.500.11970/99567.

Baraldi, p., Compare, M., Zio, E. 2014. Uncertainty treatment in expert information systems for maintenance policy assessment. Available at: https://re.public.polimi.it/bitstream/11311/967959/2/2014_ASOC_Baraldi_Compare_Zio_Incertezze_new.pdf

CDA (Canadian Dam Association). 2013. Dam Safety Guidelines.

Chovan, K. M., Julien, M. R., Ingabire, É.P., Masengo, E., Lépine, T., James, M. and Lavoie, P.2021. Risk assessment for tailings management. CIM Journal, 12(1), pp. 9–24. doi:10.1080/19236026.2020.1866336.

DeNeale, S.T., Baecher, G.B., Stewart, K.M., Smith, E.D. and Watson, D.B. 2019. Current State of-Practice in Dam Safety Risk Assessment. United States: N.p., Web. DOI:10.2172/1592163.

Dos Santos, R.C., Caldeira, L., Serra, J. 2012. FMEA of a tailings dam. Georisk: Assessment and Management of Risk Engineered Systems and Geohazards, DOI:10.1080/17499518.2011.615751

Drouin, M. 2009. Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-informed Decision Making. Main Report. United States Nuclear Regulatory Commission, NUREG-1855, Vol. 1

FEMA (Federal Emergency Management Agency). 2015. Federal Guidelines for Dam Safety Risk Management. Federal Emergency Management Agency, Washington, DC, p. 49.

France, J.W. and Williams, J.L. 2017. Risk analysis is fundamentally changing the landscape of dam safety in the United States. Proc. GeoRisk, ASCE, Denver, p. GSP282.

Global Tailings Review. 2020. Global Industry Standard on Tailings Management. International Council on Mining and Metals, United Nations Environment Programme, and Principles of Responsible Investment.

Hartford, D. N. D. and Baecher, G. B. 2004. Risk and Uncertainty in Dam Safety. Thomas Telford, London.

Hayhoe, K and Stoner, A. 2019. Alberta's Climate Future. ATMOS Research and Consulting. https://open.alberta.ca/dataset/89a69583-a11b-4e31-a857-b311ab6563cc/resource/17ce2d24-ba7b-466c-acd9-33a2cf6beb69/download/aep-alberta-climate-report-arc.pdf

ICOLD (International Commission in Large Dams). 2005. Risk Assessment in Dams Safety Management. A Reconnaissance of Benefits, Methods and Current Application. Bulletin 130, International Commission on Large Dams, Paris.

Islam, S., Williams, D.J., Serna, M.L. and Zhang, C. 2020. Settling, consolidation and shear strength behaviour of coal tailings slurry. International Journal of Mining Science and Technology, 30(6), pp. 849–857. DOI: 10.1016/j.ijmst.2020.03.013.

Jefferies, M. and Been, K. 2016. Soil Liquefaction – A critical state approach.

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. and Edwards, K.A.H. 2014. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. Applied Geochemistry, 51(December), pp. 229–245. DOI: 10.1016/j.apgeochem.2014.09.010.

MAC (Mining Association of Canada). 2017. A Guide to the Management of Tailings Facilities, 3rd edition

Macciotta, R and Lefsrud, L. 2020. PBRISD, Dam Safety Management Systems, And The Role Of Communication And Culture For Tailings Dam Failure Preventability. Canadian Dam association Bulletin, Vol 31. No 4.

McLeod H. N., Watts B.D., Plewes, H. 2015. Best Practices - Tailings Dam Design. Canadian institute of mining

McLeod, H., and Murray, L. 2003. Tailings dam versus a water dam, what is the design difference?. ICOLD Symposium on Major Challenges in Tailings Dams, Montréal, Quebec, Canada

Mittal, H. K. and Morgenstern, N. R. 1975. Parameters for the Design of Tailings Dams. Canadian Geotechnical Journal, 12(2), pp. 235–261. DOI: 10.1139/t75-028.

Morgenstern, N.R. (2018) Geotechnical Risk, Regulation, and Public Policy – 6th de Mello Lecture. Soils and Rocks, Sao Paulo, 41(2):107-129.

Oboni, F., Oboni, C. 2020. Tailings Dam Management for the Twenty-First Century.

Paul, A.L., Slingerland, N.M. and Beier, N.A. 2021. Developing A Precipitation Dataset for Mine Closure Modelling Using Intensity-Duration-Frequency Curves

Schafer, H.L., Beier, N.A. and Macciotta, R. 2021. A Failure Modes and Effects Analysis Framework for Assessing Geotechnical Risks of Tailings Dam Closure. Minerals 2021, 11, 1234.

Schafer, H.L. 2022. Risk Management for Tailings Dam Safety: Considerations for Long-term and Post-closure Timelines. PhD thesis. Department of Civil and Environmental Engineering, University of Alberta

Schafer, H.L., Beier, N.A. and Macciotta, R. 2022. Applying a Generalized FMEA Framework to an Oil Sands Tailings Dam Closure Plan in Alberta, Canada. Minerals 2022, 12, 293.

Schafer, H.L., Beier, N.A. and Macciotta, R. 2019. Closure and the Long-Term Behaviour of Tailings Dams: Using Industry Experience to Fill in the Gaps. In Proceedings of the 72nd Canadian Geotechnical Conference, St. John's, NL, Canada, 29 September–2 October 2019.

Schafer, H.L., Macciotta, R. and Beier, N.A. 2020. Tailings dam closure scenarios, risk communication, monitoring, and surveillance in Alberta. CIM J, 11, 80–90.

Silva, F., Lambe, W. T. and Marr, W. A. 2008. Probability and risk of slope failure. Journal of Geotechnical and Geoenvironmental Engineering American Society of Civil Engineering, 134(12), 1691–1699.

Silver, N. 2015. The Signal and the noise: Why so many predictions Fails- but Some Don't.

Slingerland, N. 2019. Geomorphic landform design and long-term assessment of tailings storage facilities in the Athabasca oil sands. PhD thesis. Department of Civil and Environmental Engineering, University of Alberta. DOI: 10.7939/r3-aptk-7617.

Slingerland, N., Beier, N.A. and Wilson, G.W. 2018. Landscape Evolution Modelling of Large Sand Tailings Dams. In Proceedings of the 2018 International Mine Closure Conference, Leipzig, Germany, 3–7 September 2018.

Slingerland, N., Isidoro, A., Fernandez, S., Beier, N.A. 2018. Geomorphic Analysis for Tailings Dam Design in Consideration of a 1000-Year Closure Design Life. In Proceedings of the 2nd International Congress on Planning for Closure of Mining Operations, Santiago, Chile, 7–9 November 2018.

Stahl, R.P. 1996. Characterization and Natural Processes Enhancing Dry Landscape Reclamation of Fine Processes Mine Wastes.

USACE (US Army Corps of Engineers). 2014a. Safety of Dams - Policy and Procedures. ER 1110-2-1156, US Army Corps of Engineers, Washington, DC, p. 528.

Williams, D.J. and Carter, J.P. 1991. Two-Dimensional Finite Element Analysis Of Trail Embankment On Coal Mine Tailings

7. Appendix A. Generalized FMEA Charts for Various Elements of External Tailings Facilities in Alberta

7.1. Table A- 1: Drain element G- FMEA chart

Element	**Failure Mode Identification**	**Failure mode description**	**Potential Trigger/Cause**	**Screening assessment of failure mode**	**Failure effects**
Perimeter ditch	1	Blockage (partial or full)	Sedimentation, sloughing/slope failure of walls, beaver dam, continuous build up of ice (icing)	Is there erosion protection in place? What is the slope of the ditch? Is it sufficient to keep particles suspended? What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before? Are there beavers in the area? Is the mine located in an area that could experience icing?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	2	Reduction in cross-sectional area	Sloughing/slope failure of walls, excessive vegetation	What is the slope of the side slopes? What is the strength of material? Have there been failures in this material before? Will the ditch regularly have water running through it or will it stay dry for a portion of the year? Are there deterrents in place to prevent the growth of vegetation?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, reduced capacity, erosion, potential flooding, blockage of drain outlets, toe erosion, discharge of process affected water to the environment
	3	Change in slope	Erosion, differential settlement	Is there erosion protection in place? Does the material have the potential to consolidate or settle over time? Is it a cut into natural ground or is the material placed?	Change to water discharge velocity, creation of secondary channels, localized areas of erosion, instability of dam
	4	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Rise in phreatic surface, increase in seepage, pond on reclamation surface, internal erosion, global instability, reduced capacity, erosion, potential flooding, blockage of drain outlets,

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
					toe erosion, discharge of process affected water to the environment
Pipes (perforated and non-perforated)	5	Breakage of pipe	Break in pipe, buckling, physical degradation	Is the pipe capable of breaking, buckling, and/or physically degrading over time?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	6	Pipe clogging	Biological, chemical, particulate clogging	Is chemical, biological, or sediment clogging possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	7	Clogging surround (woven sock or sand and gravel bed)	Biological, chemical, or particulate clogging	Is it possible for the material surrounding the pipe to become clogged?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	8	Blockage at outlet	Blockage from perimeter channel or other (snow, debris, etc.)	Is the pipe outlet close enough to the base of the perimeter channel that it could become blocked?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface,

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
					internal erosion, global instability
	9	Breakage of connection between a drain and outlet pipe	Overloading, degradation of connection, poor installation	How are the drain and outtake connected?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Granular materials	10	Erosion from flowing water	Increase in seepage gradients, development of preferential flow paths adjacent to drain (i.e. burrowing from animals, cracks)	Could cracks develop along drains? Is the site known for having issues with burrowing animals? Is the material erodible?	Decreased capacity of drain resulting in failure, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, erosion on downstream slope
	11	Clogging	Biological, chemical, particulate clogging	Is chemical, biological, or sediment clogging possible? What the is grain size distribution?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
	12	Failure to meet drain criteria	Change in material properties, including permeability due to aging, change in gradation due to movement with seepage, weathering/degradation	To what extent is aging and weathering/degradation of the material possible?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	13	Obstruction of drainage at outlet	Snow and ice blocking outlet	Will an obstruction prevent the drain from performing as intended? Is the outlet protected from a blockage?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	14	Deformation leading to reduction in drain capacity	Slow and continuous deformation under long lasting shear and pressure forces from consolidation of overlying material	How much deformation is expected over time as the materials above the drain consolidate and settle? Has the impact on the drain been considered?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	15	Crushing/breakage of granular drain	Overloading drain, settlement of the dam	How much settlement is expected to occur over time? Was settlement accounted for in the design? Will the drain continued to be loaded?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
Geosynthetics	16	Aging	Degradation of geosynthetic over time (temperature, oxidation, hydrolytic, chemical, biological, radioactive, etc.)	Is the geosynthetic capable of aging in the given time frame? Have sufficient tests been performed to investigate this?	Brittle rupture of geosynthetic, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	17	Creep deformation	Slow and continuous deformation under long lasting shear and pressure forces from consolidation of overlying material	How much deformation is expected over time as the materials above the geotextile consolidate and settle? Has the impact on the geosynthetic been considered?	Reduction in thickness leading to reduction in drain capacity or shear failure od drain if in-place deformation reaches a critical value, lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Geosynthetics	18	Clogging	Biological, chemical, particulate clogging	Are there dispersive soils present? Are there ferrous soils? Does the permeant contain oily waters or sludge? Is there turbid water with high suspended solids? Is there potential for chemical precipitation or biological growth? What is the end land use (does it involve agriculture or sewage systems that could result in clogging)? Is sediment capable of clogging the drain? What is the grain size distribution?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
	19	Blockage	Intrusion of adjacent materials (i.e. geotextile), blockage or downstream or exit surface caused by sedimentation, vegetation, etc.	Does the downstream or exit surface of the geosynthetic have the potential to be blocked and prevent drainage from sediment, vegetation, ice, snow, etc.? Could adjacent materials 3impeded movement of water to the geosynthetic?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
	20	Blinding where fine grained soils are prevented from entering the geotextile, which creates a filter cake	Formation of a filter cake at the interface of the geosynthetic from coarse particles being retained by the geotextile and intercepting fine particles migrating from the soil	Is the geosynthetic in intimate contact with the soil? Have all appropriate filter criterion been followed during design?	Lack of control of phreatic surface (potential rise in phreatic surface), increase in seepage, pond on reclamation surface, internal erosion, global instability, release of water into downstream shell, erosion on downstream slope
Low permeability cores	21	Hydraulic fracture	Decrease in total stress (i.e. differential settlement, arching in narrow cores), increase in porewater pressure	Is there a narrow core? Is there the potential for excessive differential settlement that could lead to a decrease in total stress? Is there the potential for an increase in porewater pressure? Is there an effective downstream filter to prevent internal erosion of the core?	Cracking, internal erosion, global instability
	22	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect. Presence of widely gap graded or non-plastic gap graded soils.	Is the material widely gap graded or gap graded non plastic? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
	23	Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation, starter dyke, or other tailings materials or differential settlement; tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, development of a pipe
	24	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse grained and fine grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine grained soil? Is there a filter in place? Is there an effective downstream filter to prevent internal erosion of the core? Is there an effective downstream filter to prevent internal erosion of the core?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the PWP (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
	25	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Does the PWP rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle? Is there an effective downstream filter to prevent internal erosion of the core?	Slumping of downstream slope, translational slide, rotational slide
	26	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, or downstream; surface erosion of downstream slope; excessive and uncontrolled seepage through foundation resulting in erosion of toe; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there potential for anthropogenic contributions (i.e. excavations or construction)? Erodibility of material? Is there an effective downstream filter to prevent internal erosion of the core?	Slumping of downstream slope, translational slide, rotational slide

Element	Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
	27	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur? Is there an effective downstream filter to prevent internal erosion of the core?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks above starter dyke, internal erosion, overtopping

7.2. Table A- 2: Foundation FMEA

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
1	Heave (seepage forces create zero effective stress condition)	Embankment loading, excessive rainfall, embankment seepage	What are the current hydraulic gradients and maximum possible due to geometry? What are the materials present? Are there cohesionless soils confined by an overlying lower permeability layer?	Global instability
2	Vertical deformation from collapse of karst formation	Collapse of karst formation	Is there karst present in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problem than longitudinal cracks) in dam, internal erosion in dam, crest subsidence

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
3	Vertical deformation caused by settlement of material	Consolidation	Will the materials in the foundation consolidate over time? How much consolidation has already occurred? Does the material have the potential to collapse?	Cracking (transverse cracks - perpendicular to dam crest are larger problem than longitudinal cracks) in dam, internal erosion in dam, crest subsidence
4	Excessive/uncontrolled seepage through foundation or foundation/dam contact	Excessive rainfall	Is there potential for seepage through the foundation? What is the permeability of the materials?	Erosion of downstream toe, increase in PWP in dam, global instability
5	Shear failure along pre-existing shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Are there pre-existing shear planes? Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
6	Shear failure along new shear plane from changing shear stress	Loading/unloading of foundation, earthquake, subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there the potential for anthropogenic loading or unloading events? Is the material erodible?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
7	Shear failure along pre-existing shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Are there pre-existing shear planes? Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
8	Shear failure along new shear plane from changing shear strength	Degradation/weathering, porewater pressure change, progressive failure of strain softening materials, brittle failure of contractive materials	Is there the potential for degradation or weathering of the material? Is the material strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide, static liquefaction
9	Internal erosion in foundation or dam/foundation contact from global backward erosion	Failure of soil above or around a backward erosion pipe to hold a roof, heave, high hydraulic gradients, design/construction defect. Presence of non-plastic soils in the foundation.	Is there non-plastic soils in the foundation?	Static liquefaction, global instability, unravelling/sloughing of downstream face, sub vertical cavities
10	Internal erosion in foundation or dam/foundation contact from backward erosion piping	Heave, high hydraulic gradients, design/construction defect. Presence of non-plastic soils that are capable of holding a roof.	Is there non-plastic soils in the foundation and soils capable of 'holding a roof'?	Enlargement of pipe, global instability, static liquefaction

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
11	Internal erosion in foundation or dam/foundation contact from contact erosion	Parallel flow in coarser layer to the interface between the coarse grained and fine grained soil, high hydraulic gradients, design/construction defect	Is there a contact between a coarse grained and a fine grained soil? Is the geometrical and hydraulic condition for contact erosion met?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the PWP (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
12	Internal erosion in foundation or dam/foundation contact from suffusion	High hydraulic gradients, design/construction defect. Presence of widely gap graded or non-plastic gap graded soils.	Is the material widely gap graded or gap graded non plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
13	Internal erosion in foundation or dam/foundation contact from concentrated leak	Fracture in foundation soil, hydraulic fracture, high hydraulic gradient, cracks at dam/foundation contact from vertical deformation in foundation or poor construction practices or differential settlement, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
14	Thawing of foundation permafrost	Climate change	Is there permafrost in the foundation?	Cracking (transverse cracks - perpendicular to dam crest are larger problem than longitudinal cracks) in dam, piping in dam, crest subsidence

7.3. Table A- 3: Dam Body FMEA

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
1	Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions, surface erosion	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction?	Increase in surface erosion, instability of downstream slope, global instability, change in overall

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
		on downstream slope, evolution of vegetation over time due to climate change	What is the downstream slope? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e. recreational vehicles)?	evapotranspiration and water balance impacts (infiltration versus runoff)
2	Internal erosion in dam from suffusion	High hydraulic gradients, design/construction defect. Presence of widely gap graded or non-plastic gap graded soils.	Is the material widely gap graded or gap graded non-plastic?	Global instability, seepage on the downstream slope, settlement of the crest, permeability may increase as erosion progresses or decrease if clogging occurs
3	Internal erosion in dam from concentrated leak	Cracks from vertical deformation in foundation, starter dyke, or other tailings materials or differential settlement; tunnels created by burrowing animals, hydraulic fracture, high hydraulic gradient, design/construction defects	Is there a crack or gap that could allow for a concentrated leak to develop?	Global instability, development of a pipe
4	Internal erosion in dam from contact erosion	Parallel flow in coarser layer to the interface between the coarse grained and fine grained soil, high hydraulic gradients, design/construction defects	Is there a contact between a coarse and fine grained soil? Is there a filter in place?	Global instability, static liquefaction, settlement of the crest, loss of stability or unravelling, eroded material can clog the permeable layer and increase the PWP (could result in hydraulic fracture and uplift of the downstream toe or a rise in the phreatic surface), development of a pipe
5	Dynamic liquefaction	Earthquakes, induced seismicity, construction traffic, blasting	Seismic events in area? Induced seismicity? Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted?	Global instability
6	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Does the PWP rely on drain performance? Could drains fail over time? Are the materials strain softening or brittle?	Slumping of downstream slope, translational slide, rotational slide
7	Shear failure from changing shear stress	Loading/unloading crest, toe, upstream, or downstream; surface erosion of downstream slope; excessive and uncontrolled seepage through foundation resulting in erosion of toe; earthquake; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Is there potential for anthropogenic contributions (i.e. excavations or construction)? Erodibility of material?	Slumping of downstream slope, translational slide, rotational slide

Failure Mode Identification	Failure mode description	Potential Trigger/Cause	Screening assessment of failure mode	Failure effects
8	Static liquefaction from changing mean effective stress	Change in pore pressures caused by a phreatic surface change (i.e. failure of drainage system)	Density of material (contractive or dilative)? Saturated or unsaturated? Hydraulically placed or compacted? Does control of the phreatic surface rely on drain function? Could drains become clogged or fail in the future?	Global instability
9	Static liquefaction from changing shear stress	Loading/unloading; overloading including increasing the load, construction activities at the crest, fill placement at toe; over steepening of downstream slope or toe (slumping of downstream slope from shear failure), including erosion or excavation of toe; foundation shear; shear in starter dyke; shear in other tailings materials; excessive and uncontrolled seepage through foundation resulting in erosion of toe; subsurface stress changes (geothermal development, in situ oil or gas production, wastewater injection, etc.)	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Is there a likelihood for anthropogenic contributions in the future (i.e. unexpected construction)? Is the site remote? What is the material of the downstream slope? Is there a nearby river?	Global instability
10	Static liquefaction from changing shear stress and mean effective stress	Lateral extrusion	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? Weak layers interbedded in tailings? Could the tailings 'squish' out like toothpaste during loading?	Global instability
11	Static liquefaction from long-term change in material properties resulting in changing shear strength	Changing shear strength caused by degradation/weathering, progressive failure, PWP change, failure of drains	Density of material (contractive or dilative)? Hydraulically placed or compacted? Saturated or unsaturated? To what extent could weathering or degradation of the material occur? Will it result in an increase or decrease in strength? Will a change in the phreatic surface impact the strength of the material?	Global instability
12	Surface erosion from spring sapping (headward erosion of gullies due to concentration of seepage forces at the locus of the gully which accentuates erosion)	Destruction of vegetation, increased seepage on downstream slope from failure drainage system, increased seepage from internal erosion of starter dyke or tailings deposits)	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Will seepage daylight on the downstream slope?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps

Failure Mode Identification	**Failure mode description**	**Potential Trigger/Cause**	**Screening assessment of failure mode**	**Failure effects**
13	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation, rainfall, melting of snow, wind, increased seepage on downstream slope from failure of drainage system, increased seepage from internal erosion in embankment	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps
14	Toe erosion	Flow action from perimeter ditch or nearby river, release of a dam from a beaver, flood event, river changing course over time, destruction of vegetation, excessive and uncontrolled seepage through foundation, excessive erosion from internal erosion	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection? Is there a nearby perimeter ditch or river? Is there known animal activity in the area?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in perimeter channel with sediment, development of negative drainage, development of large erosion scarps, beaver bafflers
15	Vertical deformation (differential or otherwise) from consolidation	Consolidation/settlement	Does the material have the potential to consolidate? How much consolidation has occurred already? How much is expected to occur?	Release of pore water and loss of height (potential for pond to develop on reclamation surface), development of cracks above starter dyke, internal erosion, overtopping

7.4. Table A- 4: Landform FMEA

Item/Functional Identification	**Failure Mode Identification**	**Failure mode description**	**Potential Trigger/Cause**	**Screening assessment of failure mode**	**Failure effects - end effects**
Cap	1	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), infiltration of previously unsaturated tailings that could increase vulnerability to liquefaction for materials previously considered "not flowable"
	2	Differential settlement	Consolidation, poor construction practices	Does the material have the potential to settle over time? Are there areas that have the potential to settle more that others?	Formation of ponds on reclamation surface, failure to direct surface water runoff towards drainage channels, development of cracks, formation of preferential flow paths, localized depressions, infiltration of previously unsaturated tailings that could increase vulnerability to liquefaction for materials previously considered "not flowable"
Infilled material	3	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)

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	4	Differential settlement	Consolidation, poor construction practices	Are there areas that have the potential to settle more than others?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), failure of drainage channels to behave as intended, localized depressions
Hummocks	5	Shear failure from changing shear stress	Loading/unloading crest, toe, slopes surface erosion, failure of underlying underlying material to support hummock	Is there potential for anthropogenic contributions (i.e. excavations or construction)? Erodibility of material?	Slumping, translational slide, rotational slide, blockage of drainage channels
	6	Shear failure from changing shear strength	Degradation/weathering, porewater pressure change, change in permeability over time, failure of drains, progressive failure of strain softening materials, brittle failure of contractive materials	Is there potential for weathering or degradation of materials? Are the materials strain softening or brittle?	Slumping of slopes, translational slide, rotational slide, blockage of drainage channels
	7	Surface erosion from wind and overland flow resulting in rills, gullies, or sheet erosion	Destruction of vegetation, rainfall, melting of snow, wind	Is the material susceptible to erosion? Is there a vegetative cover or erosion protection?	Slope failures (shallow surficial movement, slumps), change in downstream slope angle, blockage in drainage channel with sediment, development of negative drainage, development of large erosion scarps
Drainage channels	8	Washout of erosion protection (riprap)	Precipitation event larger than design events (including extreme of repeat events)	What precipitation event are the channels designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion? Was the erosion protection properly designed and constructed?	Excessive erosion (erosion gullies etc.), change in slope of drainage channels, erosion and release of materials underlying drainage channels
	9	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, slope failure/excessive erosion from nearby hummock	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the channels resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the drainage channel, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	10	Sand channel buoyancy	Freezing conditions in channels composed of sand	Are the drainage channels constructed of sand? Could the channel experience freezing?	Flooding

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	11	Erosion control failure	Improper design/construction, differential settlement	Do the drainage channels rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies etc.), change in slope of drainage channel, erosion and release of materials underlying drainage channel, formation of secondary channel
Outlet	12	Washout of erosion protection (riprap)	Precipitation event larger than design event (including extreme or repeat events), flood following sand channel buoyancy event in drainage channel	What precipitation event is the outlet designed for? What is the chance of exceedance over 1000 years? How susceptible are the underlying materials to erosion? Was the erosion protection properly designed and constructed?	Excessive erosion (erosion gullies etc.), change in slope of outlet, erosion and release of materials underlying outlet
	13	Blockage (complete or partial)	Debris, beaver dam, icing, sedimentation, slumping from slope failure, ingress of vegetation, increase in depositional material due to failure of erosion protection in drainage channels upstream	Are there beavers in the area? Is there a chance for a slope failure? Could debris be carried downstream and deposited in the outlet resulting in a complete or partial blockage? Is the mine located in an area that could experience icing?	Formation of a pond upstream of the outlet, blockage breakthrough resulting in flooding, overtopping from pond formation, revert back to a pond, piping through dam (increase in seepage forces and gradient)
	14	Sand channel buoyancy	Freezing conditions in channels composed of sand	Is the outlet constructed of sand? Could the channel experience freezing?	Flooding
	15	Erosion control failure	Improper design/construction, differential settlement	Does the outlet rely on erosion control for stability? Is there the chance for differential settlement of the channel?	Excessive erosion (erosion gullies etc.), change in slope of outlet, erosion and release of materials underlying outlet, formation of secondary channel
Vegetative cover	16	Destruction of vegetation	Suffocation by eroded material, forest fires, pests and disease, climate change, large storm event, anthropogenic contributions,	Does the resistance to erosion rely on the vegetation? Is the area susceptible to forest fires? Are there pests/disease that could lead to vegetation destruction? Is the area remote? Are there surrounding communities that could lead to destruction of vegetation (i.e. recreational vehicles)?	Increase in surface erosion, deposition of material in drainage channels that could lead to a blockage via sedimentation, development of negative drainage on reclamation surface, ponding of water near dam crest, internal erosion (increase in seepage forces and hydraulic gradient)
Tailings	17	Excessive settlement	Consolidation	Does the material have the potential to settle over time?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients)

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	18	Differential settlement	Consolidation, different material properties/infilling techniques etc.	Are there areas that have the potential to settle more than others?	Formation of ponds on reclamation surface, overtopping, piping (increase in seepage forces and gradients), failure of drainage channels to behave as intended, localized depressions