ADAPTATION OF INDUSTRIAL RISK ASSESSMENT FRAMEWORK TO ADDRESS DAMS AND TAILINGS STORAGE FACILITIES SAFETY RISKS

Gilles Bourgeois, ing., P.Eng., M.Sc.A., WSP, Québec, Québec, Canada
Lucas Duarte, ing., M.Sc., Vale S.A., Montréal, Québec, Canada
David Bleiker, P.Eng., WSP, Mississauga, Ontario, Canada
Sean D. Hinchberger, Ph.D., P.Eng., SDH Engineering, St. Catherines, Ontario, Canada
Robert A. Cross, M.Eng., P.Eng., P.Geo., Klohn Crippen Berger, Toronto, Ontario, Canada

ABSTRACT

Risk Management practices are well established in many industries. Mining companies manage the risks associated with a variety of geotechnical and industrial facilities at their properties, including process plants, storage piles, open pits, underground works, and critically: water dams and tailings storage facilities (TSF). For these owners, adopting a unified risk management framework applicable to these facilities enables personnel to identify, quantify, and manage risk using the same processes and language improving risk visibility and understanding throughout the organization. In 2020, Vale embarked on the process of adapting their existing Hazard Identification and Risk Analysis (HIRA) methodology, developed for industrial facilities, to be applied to the dams and TSFs owned and operated by Vale globally. The updated HIRA methodology, as applied to dams and TSFs, incorporates modern dam safety practices, and combines these within the International Council on Mining and Metals (ICMM) Risk Management Framework, focusing on Critical Control identification and Critical Control Management. This paper provides an overview of Vale's HIRA process for dams and TSFs and discusses the challenges and benefits of implementing the process globally within Vale. It also illustrates how the Best Available Practices from the industrial process engineering and dam engineering fields can be combined to achieve improved communication, risk visibility and streamlined risk management processes. Up to the end of 2022, the process has been used for over 125 High, Very High, and Extreme Consequence dams operated by Vale globally with a summary of the outcome presented in this paper.

RÉSUMÉ

Les pratiques de gestion des risques sont bien établies dans de nombreuses industries. Les sociétés minières gèrent les risques associés à diverses installations géotechniques et industrielles sur leurs propriétés, y compris les usines de traitement, les dépôts de matériaux, les fosses à ciel ouvert, les travaux souterrains et, surtout, les barrages et les installations de stockage des résidus miniers (TSF). Ainsi, l'adoption d'un cadre unifié de gestion des risques applicable à ces installations permet au personnel d'identifier, de quantifier et de gérer les risques en utilisant les mêmes processus et le même langage, améliorant ainsi la visibilité et la compréhension des risques dans l'ensemble de l'organisation. En 2020, Vale s'est lancée dans le processus d'adaptation de sa méthodologie existante d'identification des dangers et d'analyse des risques (IDAR), développée pour les installations industrielles, pour être appliquée aux barrages et TSF détenus et exploités par Vale dans le monde. La méthodologie actualisée de l'IDAR, telle qu'elle est appliquée aux barrages et aux TSF, intègre les pratiques modernes de sécurité des barrages et les combine dans le cadre de gestion des risques du Conseil international des mines et métaux (CIMM) en mettant l'accent sur l'identification des contrôles critiques et la gestion des contrôles critiques. Cet article donne un aperçu du processus d'IDAR de Vale pour les barrages et les TSF et discute des défis et des avantages de la mise en œuvre du processus à l'échelle mondiale au sein de Vale. Il illustre également comment les meilleures pratiques disponibles dans les domaines de l'ingénierie des procédés industriels et de l'ingénierie des barrages peuvent être combinées pour améliorer la communication, la visibilité des risques et rationaliser les processus de gestion des risques. Jusqu'à la fin de 2022, le processus a été utilisé pour plus de 125 installations à conséquences élevées, très élevées et extrêmes exploitées par Vale dans le monde avec un sommaire des résultats présentés dans cet article.

1 INTRODUCTION

Vale is an integrated mining company with significant mining, processing/beneficiation plants, rail, port, hydroelectric, shipping, and many other assets. All of these areas manage risks and make use of risk assessments, controls, and critical controls. There is also a long history of dam and tailings management practitioners undertaking risk assessments and developing controls. In our experience, the tailings management industry has typically developed its risk assessment tools independent of other areas. In fact, the tools used in the tailings industry will differ between practitioners and furthermore the same practitioners may change tools between sites. While there can be good reasons for variations, the variations do not allow for evaluation or comparison of risks across a business or even across similar dams in the owner's portfolio. For example, there is no way for management to compare the risk of a dam failure at different sites or to a ship sinking, a train derailment, etc.

Identifying and evaluating risk is important, however that alone does not manage risk. Controls and critical controls need to be identified and, if necessary, developed, as well as implemented. While this is good management practice, it is also clearly required in Requirement 6.4 of the Global Industry Standard on Tailings Management.

Vale identified benefits in developing a risk assessment process consistent with other parts of their business. Namely these benefits include:

- Comparison of risks across the company.
- Common risk and risk management nomenclature across the company.
- Clearly identify and provide repeatable rationale for controls and critical controls.

The objectives of adapting the risk management process for dams and tailings storage facilities were to:

- Develop a risk management framework consistent with other Vale businesses. This necessitated the following items to be consistent with other Vale businesses:
    - Risk consequence classification system.
    - Guidance for estimating likelihood or probability.
    - Process to identify, develop and document critical controls.

- Implement the risk management system across the dams in Vale's portfolio. This includes:
    - Hydroelectric facilities.
    - Tailings facilities.
    - Water management facilities.
    - Sediment collection facilities.

- Institutionalize the process so that it becomes "the way things are done". This requires:
    - Process documentation.
    - Training of Vale operations to allow them to update or undertake the process without necessarily using external consultants.
    - Managers see value in the process and the output.

The main focus of this paper is on the first objective.

2 RISK MANAGEMENT FRAMEWORK – OVERVIEW

The risk management framework adopted by Vale for dams and TSFs is based on the ICMM Health and Safety Critical Control Management – Good Practice Guide (ICMM 2015, 2022 – Fig .1) and in ICOLD Bulletin 130 (ICOLD 2003). It is notable the ICMM Health and Safety Critical Control Management (CCM) framework had been implemented by Vale in their industrial or process operations. Also, Vale's management system, which is referred to as the Vale Production System (VPS), requires standardization (Vale 2023). As such, a consistent framework and language was required for risk management across all Vale operations.

Figure 1: ICMM Health and Safety Critical Control Management Framework

The ICMM Critical Control Management framework relies on a nine-step process (see Fig. 2), which was subsequently modified by Vale to ten-steps as described below. Steps 1-6 are referred to as Hazard Identification and Risk Analysis (HIRA) by Vale. A HIRA involves the study of a system, process, or structure to identify Material Unwanted Events (MUEs). An MUE is any unwanted event with consequences that exceed a threshold defined by Vale as warranting the highest level of attention.

For Dams, a standard set of MUEs was defined:

- Dam Failure by Overtopping.
- Dam Failure by Instability.
- Dam Failure by Piping.
- Dam Failure by Erosion.
- Uncontrolled Discharge.
- Public Access to Danger Zone.

It is worth noting that MUEs related to Public Access to Danger Zones are mainly identified on hydropower facilities where recreational activities both upstream and downstream of facilities are more common than would be found on a mining site, for example.

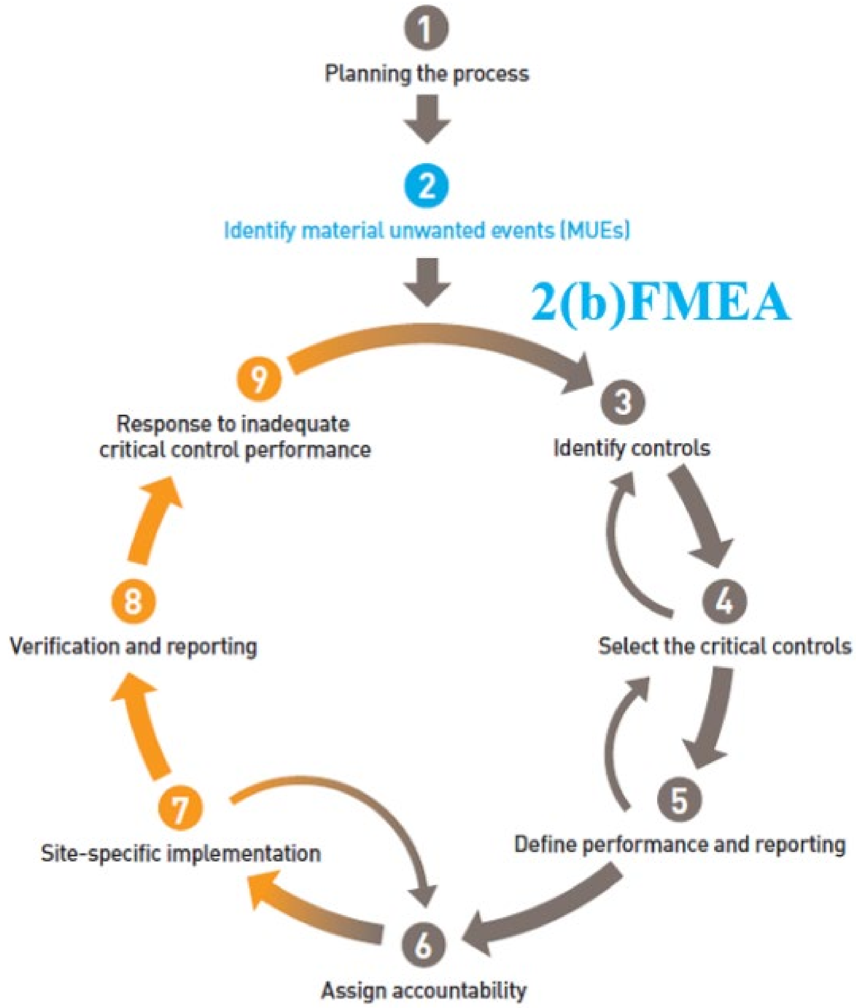

Figure 2: HIRA Process Flow Diagram

At Vale, the Critical Control Management framework for dams and TSFs was implemented by conducting a Failure Modes and Effects Analysis (FMEA) after the MUE identification (see Fig. 2). During the FMEA, the dam or TSF system was broken down into functional components, initiating events were developed starting with the failure of each functional component, and the follow-on events were mapped to the MUE, defining the causal pathways. The causal pathways support risk analyses, and are used to assess the existing controls, and assist with developing a Cause/Threat statement for risk registration in Vale's enterprise risk management system as bowties (ICMM 2015, 2022). The Critical Controls were identified during the risk analysis by comparing the assessed inherent risk for an MUE, i.e. without the control, with the residual risk, i.e. with the control. Critical Controls significantly reduce the residual risk compared to the inherent risk.

After identifying the MUEs, Failure Modes, and Critical Controls, Vale's Risk Management efforts focus on ensuring that the Critical Controls are implemented, effective, and functioning. The overall process meets two requirements: It combines good practice from process and industrial engineering (ICMM 2015, 2022) with modern dam safety practice (ICOLD 2003) and it ensures uniform risk management processes and procedures across all Vale businesses. The following section describes the process in detail.

3 THE HIRA PROCESS FOR DAMS AND TAILINGS STORAGE FACILITIES

The following four key assumptions for risks are as applicable to dams and tailings management as they are to other mining processes:

1. Material Unwanted Events (MUEs) are known.
2. Risks and controls are known. Problems are generally a failure to effectively implement the controls.
3. More is less. If everything is important, then nothing is important.
4. Some things are more important.

Recognizing the similarities between tailings management and other mining processes helps confirm the validity of the ICMM process shown in Figure 2. However implementing the process required organizational effort and identifying a corporate champion was integral to the planning process and was necessary prior to engaging consultants. The champion expended significant effort to:

- Achieve alignment and commitment of senior management.
- Ensure appropriate resources and sense of urgency would be provided to the initiative to achieve the goals within a reasonable timeframe.
- Develop norms (policies and procedures) were for the overall HIRA process as well as the individual steps (e.g., risk assessment).
- Implement meaningful change and risk management, including integration with Operations. At the conclusion of the work Operations needs to accept and act upon the outcomes of the process, or the effort would have been academic. Consequently significant effort was required to achieve operations "buy-in".
- Convey a consistent message to key participants and stakeholders. People are busy and the process requires they disrupt their normal workflow to prepare for and participate in risk assessments and critical control development at a minimum. Especially as, generally, there were follow-up actions required from participants and stakeholders.

Implementing a new process is always challenging. Without planning to ensure commitment from the Vale stakeholders, the initiative may not have made it through the most challenging moments early in implementation.

While the corporate champion was integral to aligning Vale's internal stakeholders they also:

- Developed the integrated schedule.
- Developed a set of common MUEs.
- Drove frequent meetings to update and improve the process while workshops were on-going.

3.1 Risk Assessment

A control prevents or mitigates an unwanted event and therefore lends itself to a risk assessment approach. A critical control is a control that, if missing, significantly increases the risk of an unwanted event, or prevents more than one unwanted event. Therefore identifying critical controls also lends itself to a risk assessment approach. Vale selected a Failure Modes and Effects Analysis (FMEA) as the most suitable risk assessment format for the system. FMEAs are widely used in a variety of industries and have the advantage, as a qualitative risk assessment tool, of not requiring precise estimates of consequences or likelihoods, while allowing for identification and ranking of risks. They also require significant resources, as the relevant subject matter experts need to be together to discuss the credible failure modes and their consequences.

For Vale's HIRA process, Vale's operating team, internal subject matter experts, the Engineer of Record team, and Vale's HIRA consultant all attended the HIRA workshop. Vale provided reports and background data ahead of the HIRA workshop which were reviewed and discussed ahead of time by the HIRA consultants Subject Matter Experts (SMEs). The HIRA facilitator (consulting team) pre-populated the FMEA work sheets with MUE's, mechanisms and questions/prompts to facilitate the workshop. There was always an opportunity for workshop participants to add additional risks.

It is worth noting that the original planning included conducting the HIRA workshops on-site. Due to the global COVID-19 pandemic this was switched to remote. "Site visits" were generally conducted with drone video and photographs. Eventually, as health and safety conditions permitted, local in country personnel from the HIRA consultant conducted site visits in addition to photographs and/or video for remote participants.

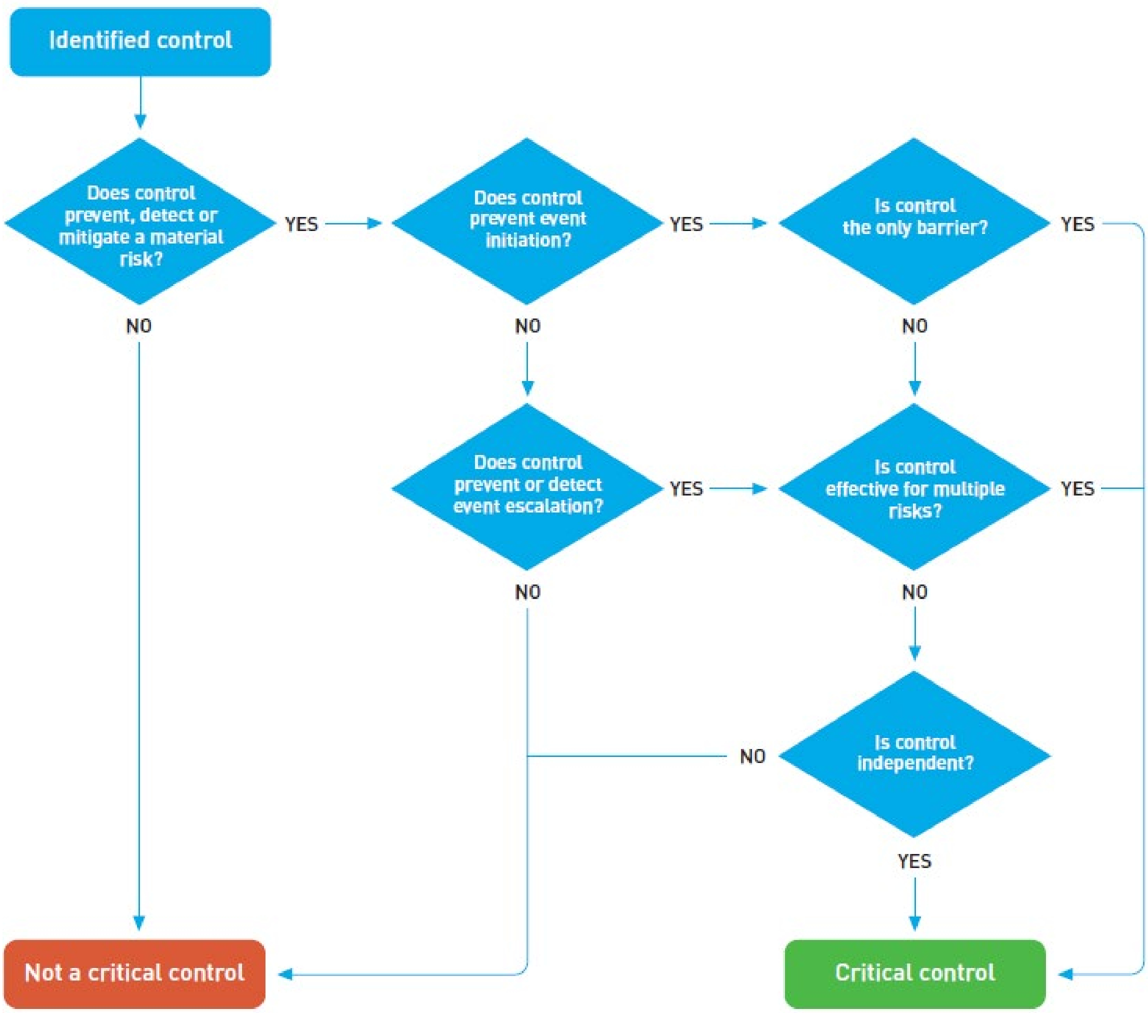

Figure 4: Critical Control Definition (ICMM 2015)

A documented and repeatable rationale for defining critical controls was developed utilizing the graphical definition shown in Figure 4. To assist in the assessment, the HIRA risk workshops initially assessed the residual risk, with the existing controls in place. The inherent risk was then evaluated assuming the controls were not in place. By assessing the residual and inherent risks, the first two decision steps in the graphical critical path definition (Figure 4) could be evaluated, and the rationale and decisions documented.

If there were unacceptable risks in the residual condition, then additional critical controls were identified, and the forecast residual risk was evaluated. The evaluation of forecast residual risk confirms that the risks can/will be reduced into Vale's acceptable range as well as serving to document the rationale for determining the controls introduced are critical controls.

While the process was executed starting with residual risk, progressing to inherent risk and then finally to forecast residual risk, the risk can also be thought of as a progression from no controls (inherent), current controls (residual) and including future controls (forecast residual) (Figure 5).

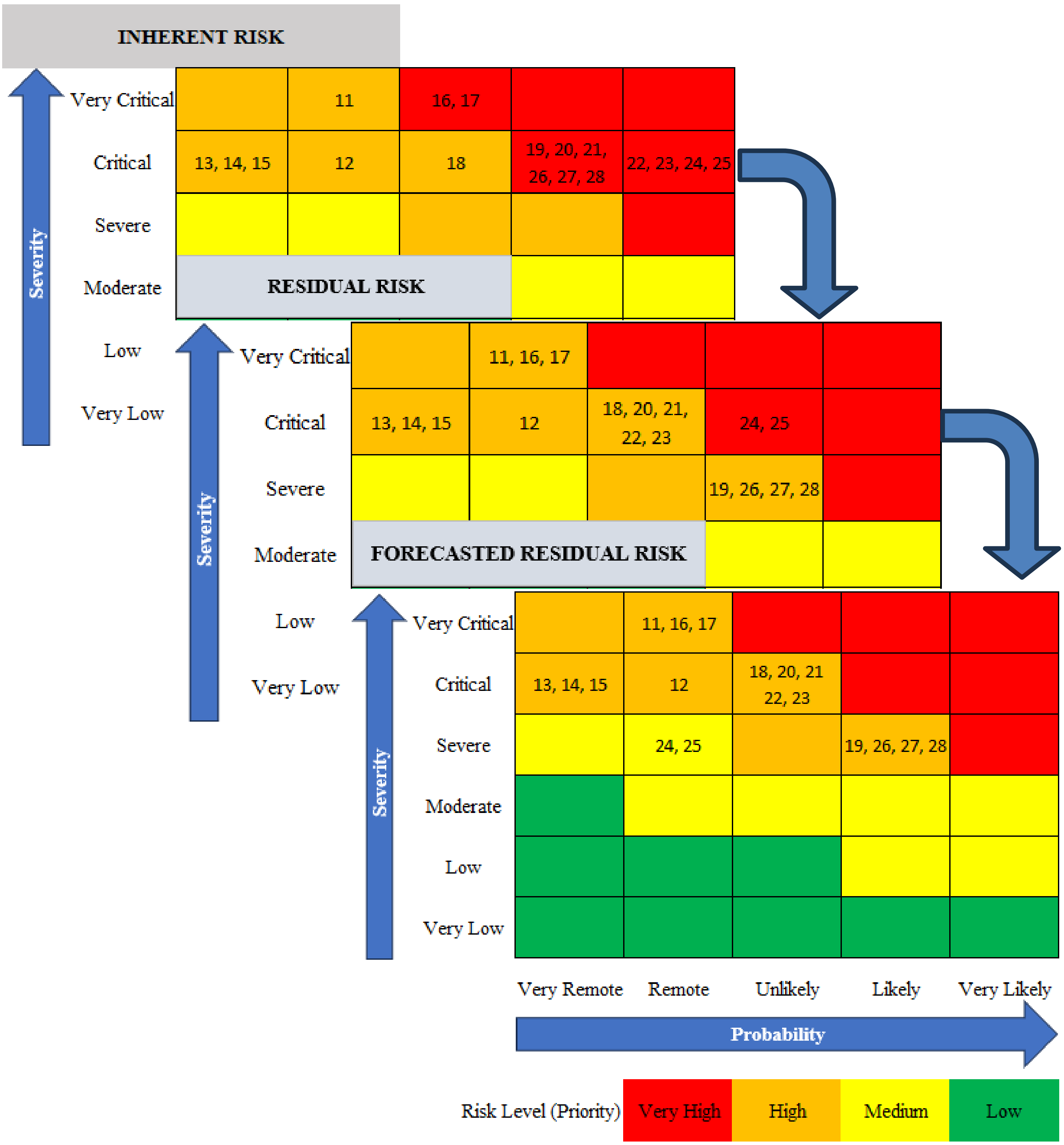

Figure 5: Typical Risk Assessment outcome from HIRA Process
(with numbers in the risk matrices representing the ID of a specific failure mechanism)

Once the critical controls were identified, "one-pagers" were developed (Figure 6).

1 What is the name of the critical control for diesel particulate overexposure (MUE)? Enclosed cab on mining equipment		
2 What are its specific objectives related to the MUE? To restrict the access of diesel particulates into the operators' environment to levels well below the occupational exposure limit		
3 What are the critical control performance requirements to meet the objectives?	**4 What are the activities within the management systems that support having the critical control able to do what is required?**	**5 What can be sampled from the set of activities for verification, providing a clear image of the critical control status?**
Positive pressure cabin environment maintained to level that prevents ingress of diesel particulates Pressure differentiator indicator that alarms when pressure drops below critical level	Scheduled maintenance and calibration of indicator according to manufacturer's requirements	Review maintenance and calibration records Review alarm log and corrective action taken
Air intake filter operating at greater than 99% efficiency	Pre-shift filter housing inspection for damage Filter inspection at planned maintenance every 500 hours Filter change-out every 1,000 hours	Review documented pre-start inspections Review 500-hour inspection records Review 1,000-hour change-out records
6 What is the target performance for critical control? 100 per cent of inspection and tests either satisfactory or repair is done before truck is put back into operation		
7 What is the critical control performance trigger for shutdown, critical control review or investigation? 5 per cent of inspections and tests indicate cab ventilation issues that cannot be resolved or are not resolved before truck returned to service		

Figure 6: Standard template for Critical Control One-Pager (adapted from ICMM 2022)

3.2 Critical Controls Development for Dams and TSFs

As identified previously, a steering committee generally consisting of the Vale champion and the HIRA facilitators regularly convened. Through discussions, this group identified similarities in the critical controls which in addition to validating the assumption that the risks and controls are generally known, allowed critical control templates to be developed using the experience from HIRAs completed to that time. While usually only 5-7 critical controls were required per facility, approximately 24 critical control templates were developed to cover the range of controls implemented.

The critical control templates were used to develop unique critical control one-pagers for each site. Workshop participants divided into teams and met separately to develop the critical controls. Each critical control was presented to the workshop participants for comment.

While the critical control templates were modified for Vale's purposes, other organizations would also be able to develop their own templates based on ICMM to meet their organizations requirements.

Frequently, actions were required to address "one-off" items. These actions ranged from additional studies to physical upgrades and were captured in a free form list. The risk mitigation they addressed, a description of the work required, how the work would be validated, and a timeline for the risk mitigation were all documented. Action items were included in the evaluation of the forecast residual risk.

Critical controls and action items were tracked with completion dates and dashboard alerts for follow up to keep the process progressing.

4 OUTCOMES FROM PROCESS

The HIRA process was conducted for 125 different dams including hydropower dams, tailings storage facilities, water dams, and sediment dams. Dams were distributed in Brazil (83), Canada (39), and Indonesia (3) and accounted for various types of structures, mainly categorized as tailings dams, sediment dams and water dams, as illustrated in Figure 7.

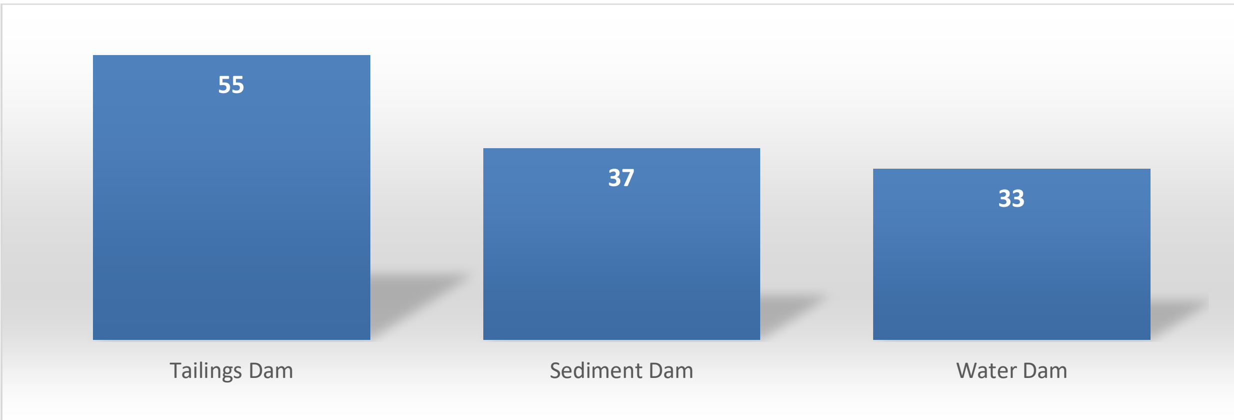

Figure 7 Distribution of structure type / purpose for the dams investigated under the HIRA Process

For most of these sites, the HIRA Process reviewed multiple dam structures. It was common for a HIRA workshop to include 4 or 5 different dam structures in one workshop. For example, at a mining site there could be a main sedimentation dam along with several internal dams, and a hydropower site could consist of a main dam and spillway, a power canal, an intake structure, and a secondary spillway, etc.

Each HIRA workshop identified on average 60 failure modes per site. For some of the more complex sites that contained several dam structures, the list of identified failure modes could exceed 200, although many of these failure modes were fairly similar from structure to structure within the facility. The resulting Material Unwanted Events for the various facilities as discussed in Section 2 were also compiled and their distribution is given in Figure 8.

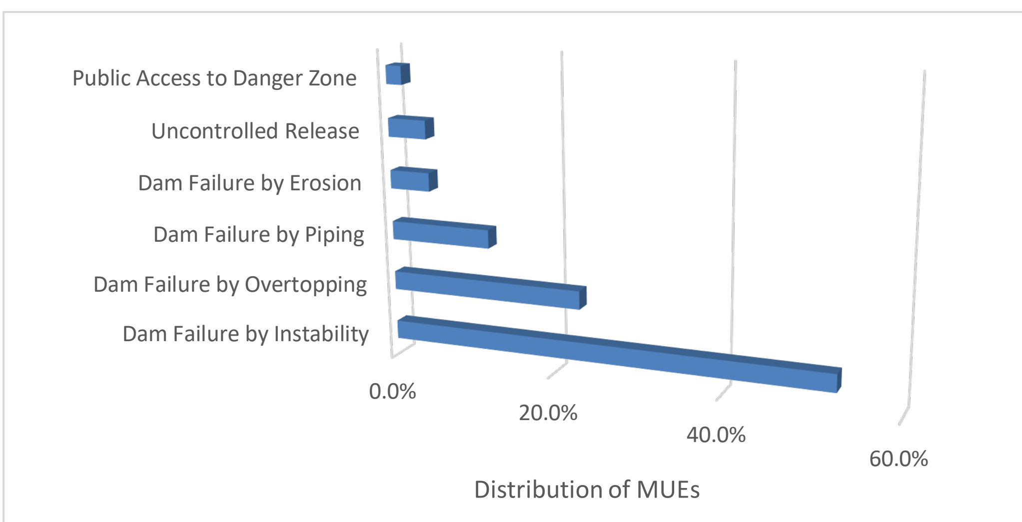

Figure 8. Distribution of Material Unwanted Events for the listed Failure Modes throughout Vale Facilities

Some of the failure modes and related MUEs are more specific to Tailings facilities such as Failure by Erosion whereas an MUE such as Public Access to Danger Zone is more typical of hydropower facilities where recreational activities in the river below the dam or in the headpond/lake is more frequent than on a mine site.

The list of key Critical Controls developed throughout the HIRA Process is summarized in Table 1. These are categorized as Operational, Performance or Public Safety Controls, along with a general Governance Control.

Table 1 Summary of the main Critical Controls developed during the HIRA Process.

Operational Controls	**Performance Controls**	**Public Safety Controls**	**Governance**
CC101: Freeboard Control Procedure	CC200: Inspection	CC300: Emergency Re sponse Procedure	CC100: Governance
CC102: Reservoir Level Monitoring System	CC201: Piezometric Monitoring System	CC301: Public Safety Access Controls	
CC103: Inflow Forecasting & Flood Routing Procedure	CC202: Seepage Monitoring System	CC302: Site Personnel Access Controls	
CC104: Decant Management Procedure	CC203: Displacement Monit oring System		
CC105: Flow Control Equipment	CC204: Independent Design Review and Verification		
CC106: Spillway or Decan t Structures	CC205: Structural Monitori ng System		
CC107: Energy Dissipatio n Equipment	CC206: Post-tensioned Anchors		
CC108: Water Quality Monitoring Procedure	CC207: Drainage Gallery or Pressure Relief Wells		
CC109: Debris Control Equipment	CC208: Slope Stabilization Controls		
CC110: Tailings Depositio n Procedure			
CC111: Potentially Acid Generating Tailings Water Cover			
CC112: Backup Dam			

5 LESSONS LEARNED

At the completion of each HIRA process, the facilitators were encouraged to compile lessons learned from the process to inform future work, as a form of continuous improvement. Several of the key lessons gleaned from this work is presented here.

One of the largest lessons learned from this process is the benefit of utilizing an already established system, even when requiring modification to apply it to a new environment. Because the framework of the HIRA was already well understood by the operators responsible for the structures reviewed, and because it used processes, forms, and vocabulary they were already familiar with, the process started from a point of familiarity. This not only engendered trust in the system by the participants, but also allowed them to feel ownership of the process and allow for the workshop to focus on what mattered – the structures, and the management of risks.

Another important lesson from the process was that active and committed participation by certain key individuals was crucial to success. To be as complete as possible required the Engineer of Record, Designer of Record, Operations Team, Risk Owner, and others to be present, engaged, and open to participation and dialogue. This required careful facilitation to encourage an environment of collaboration during the workshop, and scheduling of various parties so that they could commit their time to participate fully. The ultimate goal of the workshop was not to find consensus – as gaps were identified in the understanding of the site, or where conflict in opinion were noted, actions were taken to address these items through engineering studies.

The process itself was most successful when limits and boundaries were established in terms of what the purpose of the review was, and what elements of the structure were inside, and outside, of scope. For the scope of the review, it was important to be clear with participants that the HIRA process is not a design review, or a dam safety review. Its focus is on the understanding of risks, and the establishment and documentation of critical controls for those risks. For each HIRA, scope boundaries were set and communicated prior to the workshop, with the focus set on the structure as it existed at the time of the workshop.

The use of a variety of external consultants for the process was also beneficial. The cold-eyes review inherent in the process allowed for an inquisitive, objective process, and having different points of view between the various consultants provided a more complete, and thorough, process. In order to encourage consistency, however, prior to proceeding with the implementation of the system, a common set of failure modes was developed to allow for all sites to be screened against the same set of potential risks prior to the workshop; site-specific failure modes were added later to the FMEA during each workshop.

Keeping the focus of the process on the ultimate goal of risk reduction kept the process running smoothly. The system was centered around the definition, application, and monitoring of critical controls. The workshop participants included a significant contingent of operators, staff who manage the sites at a day-to-day level, which helped to ensure the recommendations made were practical, and realistic. The workshops also commonly included the emergency response plan team in order to gain insight into how current controls worked and could potentially be improved.

Finally, the ICMM critical control management implementation guide has been implemented and includes implementation examples for industrial process. The Vale HIRA process demonstrates ICMMs process can be adapted for geotechnical structures. Vale has successfully applied the HIRA process to tailings facilities, water dams, and sediment dams. Based on the success of this program Vale is expanding the process to other geotechnical works.

6 SUMMARY AND CONCLUSIONS

Between 2020 and 2022, Vale was able to develop a HIRA process and knowledge base specifically for dams and TSFs. In all, 125 facilities were investigated which included tailings storage facilities, sediment dams as well as water dams in Brazil, Canada, and Indonesia.

The HIRA process allowed to identify various Material Unwanted Events that could occur based on potential failure mechanisms. These were grouped in 6 categories for which Critical Controls were developed to cover either preventative controls that would reduce the likelihood of a failure mode to occur or mitigative controls that help in reducing the negative impacts of an MUE. In all, 25 main critical controls were used in the various HIRA projects centred on four categories: Operational, Performance, Public Safety and Governance, although typically there would be 6-8 of these key critical controls that would apply to any given facility depending on if it was a hydropower dam, a sediment dam, or a tailings facility.

The main benefit of conducting these HIRA for Vale is to effectively manage the risk portfolio obtaining consistency and outlook on risk levels at the global scale to allow for comparison of risks across the company, provide for common risk management nomenclature and clearly identify and provide repeatable rationale for controls and critical controls.

In the end, the success of the HIRA program for dams and Tailings facilities was eventually continued for other geotechnical structures within Vale, namely for stockpiles and open pits. In reality, such an approach to developing HIRA with identified and managed critical controls can be easily adopted for conventional water dams as well as tailings facilities. Dam and tailings facility owners would surely benefit from applying this process to their assets as it would be a useful tool within a risk assessment toolbox to consider when investigating risks for these types of structures.

7 REFERENCES

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