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Risk-informed instrumentation of tailings storage facilities

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Abstract

Surveillance through instrumentation and monitoring is crucial for evaluating performance and ensuring the safety of tailings dams. This importance has been well recognised by technical groups and peak industry bodies, which have released numerous publications emphasising the necessity and benefits of, and the developing techniques for, tailings dams monitoring. The attention to instrumentation has further intensified with the introduction of technologies such as InSAR, marketed specifically for the tailings industry, and the monitoring requirements outlined by the Global Industry Standard on Tailings Management (GISTM).

However, the collapse of the Brumadinho dam, equipped with over 100 piezometers and several inclinometers, demonstrated that an extensive surveillance program with large quantities of instruments alone cannot prevent dam failures. Moreover, there is no one-size-fits-all solution for surveillance programs. A standardised approach to instrumentation and monitoring is neither feasible nor beneficial as each facility has unique characteristics and risks. For safety monitoring to be truly effective it must be tailored to the specific failure modes and risk controls of the facility, ensuring that deviations from expected performance are detected early enough to provide actionable warnings.

This paper presents a robust, risk-informed framework for developing effective safety surveillance programs that allow tailings storage facilities owners to detect the deteriorating performance of tailings facilities and potential failure conditions, and which align with the tailings dam management framework adopted for the forthcoming revision of the Australian National Committee on Large Dams Guidelines on Tailings Dams.

Keywords: *instrumentation, monitoring, risk controls, surveillance*

1 Introduction

The importance of instrumentation and monitoring (I&M) as part of the broader surveillance of tailings storage facilities (TSFs) is widely acknowledged worldwide, with numerous technical guidelines and bulletins issued by national and international organisations.

As early as 1966 the International Commission on Large Dams (ICOLD) issued a bulletin on general considerations for instrumentation in earth and rockfill dams, while the Australian National Committee on Large Dams (ANCOLD) released its *Guidelines for Dam Instrumentation and Monitoring Systems* in 1983 (ANCOLD 1983).

Initially, the purpose of instrumenting dams was to provide additional data for the design and construction of increasingly larger dams constructed in the first half of the 20th century. Following dam failures in the 1960s, the objectives of instrumenting and monitoring dams expanded to include verifying the safety performance of dams during operation (ICOLD 1969). Today, ensuring that dams perform in line with their design intent and providing timely warnings of any changes that could threaten dam safety are central to contemporary TSF surveillance programs.

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Beyond safety, modern I&M programs are also essential for demonstrating compliance with regulatory requirements, as well as adherence to environmental and operational standards. Often, I&M themselves form part of the statutory requirements for tailings projects.

This paper presents the evolving objectives of I&M before focusing on the I&M concept that is directly related to the expected performance of TSFs throughout all life stages, from planning to closure. It then presents the benefits of directly associating surveillance programs with the identified risk controls and clarifies the difference between controlling risks and monitoring the facility's performance, which are often being confused.

Finally, we introduce a model for TSF surveillance centred on the innovative concept of performance envelopes. This concept is proposed as the cornerstone of the revised ANCOLD Guidelines on Tailings Dams, which the authors of this paper are actively developing as members of the ANCOLD Tailings Working Group. The model also incorporates principles from the ICOLD *Bulletin 194: Tailings Dam Safety* (ICOLD 2022), in which Jiri Herza participated as a member of the Working Group.

2 Evolving purposes of I&M

The primary purpose of instrumentation and surveillance for dams has evolved significantly over the past five decades, and this evolution can be traced through various ICOLD bulletins and other publications discussed below.

ICOLD *Bulletin 21: General Considerations Applicable to Instrumentation for Earth and Rockfill Dams* (ICOLD 1969) was the first bulletin addressing the instrumentation of dams and described instrumentation as a tool for monitoring structural behaviour during construction. The emphasis was on providing feedback to adjust design or construction as needed, driven by the rapidly increasing size of dams being constructed after World War II.

In *Deterioration of Dams and Reservoirs – Examples and Their Analyses* (ICOLD 1984), ICOLD expanded on this initial I&M aim by including identification of symptoms of deterioration early enough to prevent potential failures as one of the objectives of the I&M of dams.

ICOLD *Bulletin 60: Dam Monitoring – General Considerations* (ICOLD 1988) superseded Bulletin 21 and marked the completion of the focus for instrumentation expanding from informing design and construction to include safety during operations. This bulletin outlined the objectives for I&M in dams which align with the following points:

- safety and stability monitoring to ensure ongoing safety by detecting any abnormal behaviour or structural changes that might indicate potential risks, through tracking parameters like deformation, seepage and pressure
- verification of design assumptions to confirm that the dam's actual behaviour aligns with design assumptions, especially under variable environmental and operational conditions, allowing engineers to validate or adjust design models
- operational decision support to provide essential data for decision-making during extreme events, such as floods or earthquakes, by offering reliable monitoring data to guide responses and inform long-term strategies
- maintenance planning and risk management to assist in planning maintenance activities by identifying potential issues early, enabling proactive scheduling rather than reactive responses.

ICOLD *Bulletin 104: Monitoring of Tailings Dams* (ICOLD 1996) was the first ICOLD publication dedicated specifically to I&M of tailings dams. The foreword noted a significant contrast between the by-then mature state of water dam monitoring and the almost absent instrumentation for tailings dams. This bulletin recommended instrumentation to:

- facilitate observations directly concerning safety
- evaluate stability under current and maximum height conditions
- measure parameters to optimise tailings deposition techniques

- monitor water balance and potential pollution.

By including TSF's operational aspects, Bulletin 104 broadened the objectives of I&M beyond asset safety. It also provided specific recommendations for I&M of upstream and downstream raised dams as well as closed TSFs, including examples and case histories.

Although ICOLD issued several additional bulletins on I&M after 1996 (e.g. ICOLD Bulletin 158 [ICOLD 2018]), none specifically addressed tailings storage facilities until ICOLD *Bulletin 194: Tailings Dam Safety* (ICOLD 2022). This bulletin highlighted the importance of surveillance and monitoring as integral to risk management, closely tied to trigger action response plans (TARPs) and facility controls. It also clarified that while instrumentation is not a risk control in itself – since it does not prevent or minimise the risk of failure – it serves to confirm stable conditions and identify changes that may necessitate intervention, thereby verifying the effectiveness of risk controls.

Although the rise of compliance as an objective can be traced back to the 1980s it only made its mark on I&M of tailings facilities quite recently. The ANCOLD *Guidelines on Tailings Dams* (2012) suggested that instrumentation is necessary to verify that the facility remains in compliance with design and regulatory requirements. The GISTM then presented I&M as essential for verifying compliance with safety and environmental standards, as well as with the requirements set out in the GISTM itself. The International Council on Mining and Metals' *Tailings Management – Good Practice Guide* described the role of I&M in demonstrating compliance with both internal standards and external regulatory requirements.

I&M data also presents a valuable source for research and innovations. This was first recognised in ICOLD Bulletin 60 (ICOLD 1988) and is especially important in the age of data mining, deep learning and artificial intelligence technology, as discussed in Lecun et al. (2015).

The evolution of I&M has significantly expanded beyond its original construction-focused scope and the key objectives of contemporary TSFs' I&M programs can be grouped into the following partly overlapping categories:

- safety during construction, operation and closure
- compliance with internal and external requirements
- operational in informing tailings deposition and water management
- knowledge gain for research and development purposes

This paper focuses on the I&M's role in safety management of TSFs and presents a method of explicitly linking I&M to risk controls' effectiveness.

3 Instrumentation, monitoring and risk controls

ICOLD Bulletin 194 outlined a clear link between surveillance and risk control measures and presented the view that I&M is a means to determine if risk controls are effective. However, neither this bulletin nor other technical guidance expanded on how this link can be established in practice.

To set a relationship between risk controls and I&M, the authors proposed the following:

- Identify risk controls along the path of every failure mode.
- Articulate the effect of the risk controls under foreseeable scenarios. This is later referred to as the performance envelope.
- Select I&M measures that allow monitoring of the desirable effect of the risk controls.

Directly linking I&M with risk controls alone is not sufficient in terms of tailings safety management and actions should be clearly defined if instrumentation data indicates loss of a risk control's effectiveness. This requires a system that communicates the loss of risk control effectiveness to an appropriate person and predefined actions to be taken. This communication is typically implemented through the TARP and emergency response plan (ERP).

While the above structure may seem intuitive, the authors suggest from experience that the TSFs' risk controls, I&M programs, TARPs and ERPs are rarely linked together. This is demonstrated through the numerous and continuing failures of heavily instrumented TSFs. Examples include the failed Mount Polley TSF which had a total of nine operational inclinometers and 64 operational piezometers, including one operational inclinometer and nine operational piezometers near the failed section (Morgenstern et al. 2015). The Fundão dam, which failed in November 2015, had 13 Casagrande piezometers and nine vibrating wire piezometers clusters that recorded data up to six months prior to the failure (Morgenstern et al. 2016). The Feijao dam 1 (Brumadhino) had 113 operational piezometers in addition to an extensive suite of other instruments at the time of failure (Robertson et al. 2019).

The following sections present a proposed framework and workflow to effectively and defensibly implement the above items and ultimately achieve risk-informed design of a TSF's I&M system.

4 Rational and defendable approach to surveillance

The key to the proposed framework is the concept of TSF's performance envelopes. These envelopes are defined by sets of measurable indicators that characterise the intended performance of the TSF and its elements under foreseeable loading and operational conditions. The performance envelopes can be developed for all aspects of TSF management, including TSF safety, environmental compliance and operational requirements.

In the context of TSF safety, performance envelopes can be understood to be the explicit expression of risk controls, which should be continually assessed and reviewed considering all the criteria, objectives and assumptions associated with the TSF.

For new TSFs, performance envelopes should be developed during their design. Appropriate I&M can then be specified and installed, and the data reviewed to assess if the controls are effective and the TSF performs within the desirable envelopes.

The framework to develop performance envelopes, assess their effectiveness through I&M and rectify any issues, if required, is illustrated in Figure 1, and based on the upcoming ANCOLD Guidelines on Tailings Dams. Describing the intent and application of this framework is beyond the scope of this paper, however, an example of a risk-informed I&M implementation is provided here later. The highlighted parts of the process relate to the example provided later in this paper.

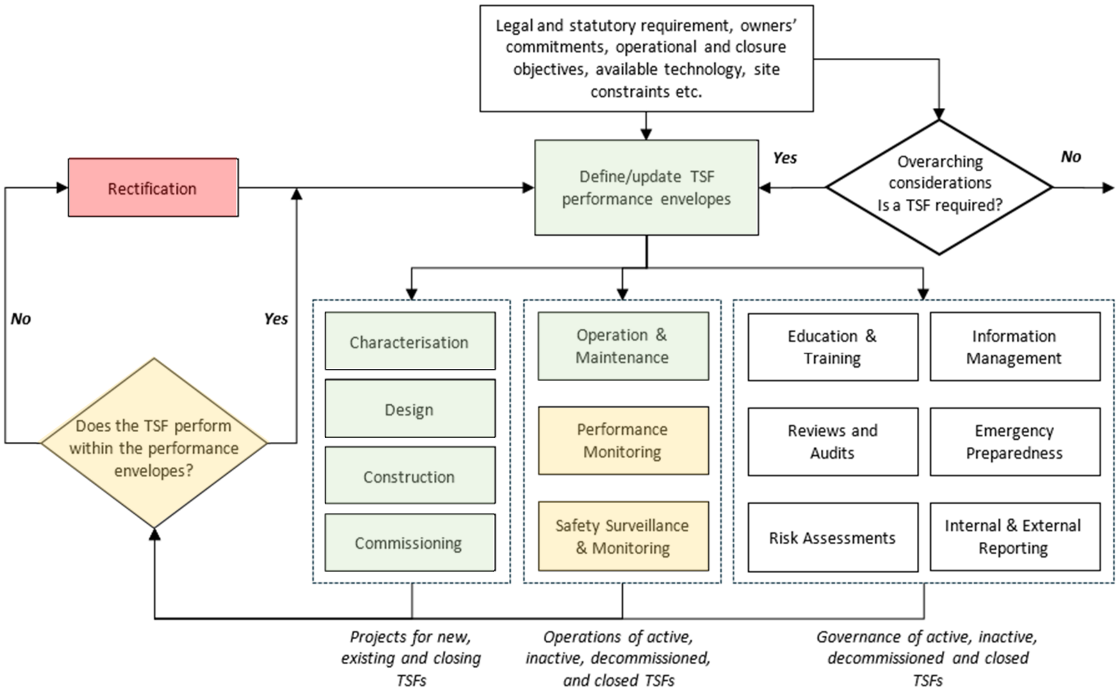

Figure 1 Tailings storage facilities safety management framework (after ANCOLD Tailings Guidelines draft, December 2024)

For existing TSFs or TSFs that are being expanded, performance envelopes can be developed as part of a risk assessment process through:

- developing all potential pathways to TSF failure and the hazards or states that are required for the pathways to actually occur and continue
- identifying all controls, both already implemented and that should be implemented, to eliminate or minimise the risk of the hazards and states that are required for the identified pathways to failure.

Once these controls are identified, reviews of already implemented controls and assessments for controls that are to be implemented should be carried out to define the required performance of the controls in order to be effective (i.e. performance envelopes).

Figure 2 presents the risk assessment framework which the authors have developed to complete such risk assessments as part of an overall TSF safety management framework. This framework is a set of interrelated activities to accomplish defensible and transparent TSF risk management. The activities related to the described process above are highlighted with blue dashes and the entire process is described in Herza et al. (2023).

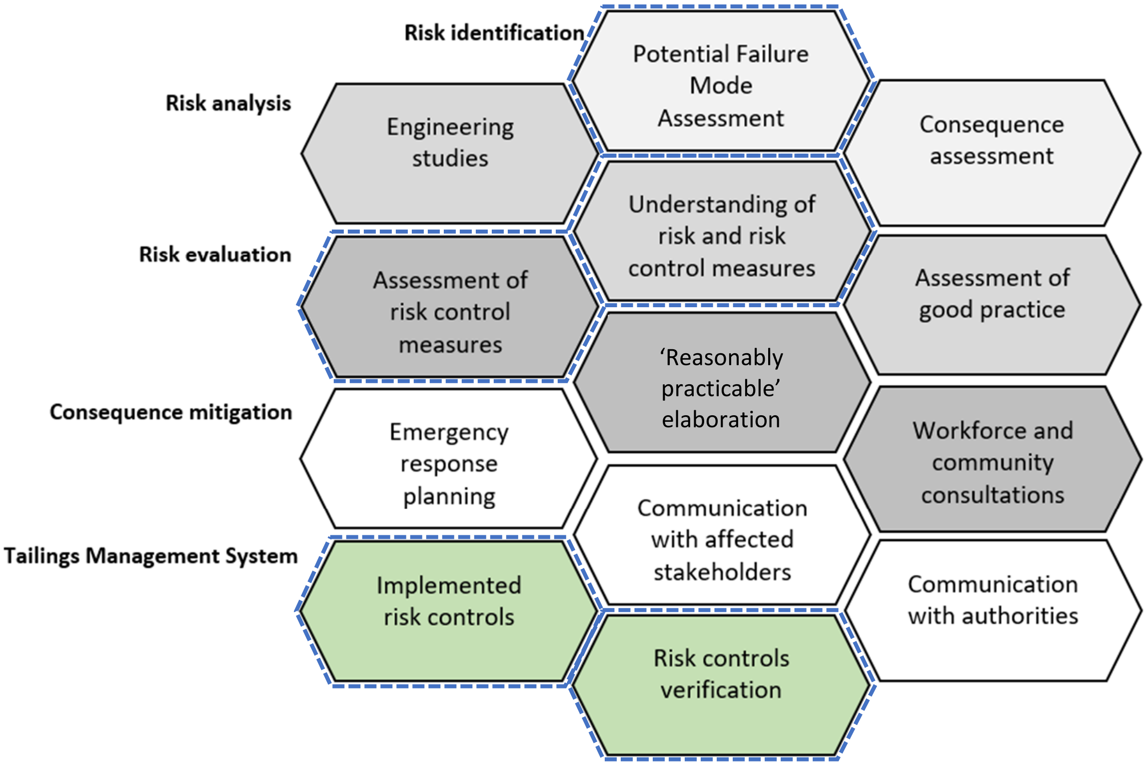

Figure 2 Risk assessment and control framework (Herza et al. 2023)

Similar to new TSFs, once performance envelopes have been developed for existing TSF safety risk controls, appropriate I&M can be implemented to provide data which will allow for the assessment of whether the controls are performing as expected. For new risk controls, I&M should be included as part of the risk control implementation.

5 Application of framework to a filtered tailings storage facility

To illustrate the development of a risk-informed design for an I&M system, consider a facility storing filtered tailings and confined by an upstream raised perimeter embankment. At this facility, inspired by a real TSF located in Western Australia, the slope stability of the perimeter embankment relies on the phreatic line being kept below the tailings supporting the upstream raises (referred to as a structural zone) under all foreseeable conditions. This key requirement was determined through appropriate testing, investigation and assessments, and the TSF was designed and constructed with specific features to control the phreatic line, referred to as supporting controls in Table 1.

As maintaining the phreatic line below predefined levels directly controls the risk of embankment instability under all conditions, the maximum phreatic surface defines a performance envelope. Piezometers are installed as an instrumentation tool to verify that controls are effective, and the phreatic conditions are maintained within the predefined envelope. The piezometers provide an early warning of rising porewater pressure that may compromise the TSF's integrity. However, it is important to note that the presence of piezometers alone does not mitigate the risk of slope instability; thus highlighting the distinction between instrumentation for control verification and the actual measures controlling the risk.

The piezometers are placed within the upstream raised perimeter embankment and internal tailings foundation zones through consideration of the expected phreatic conditions during foreseeable scenarios. They are placed in locations and at elevations which would allow for the identification of phreatic surface trends and levels that would indicate deviations from the performance envelope. All the above activities were completed as part of the elements highlighted in green in Figure 1.

As part of the safety response, if the piezometers show phreatic conditions raising beyond this envelope the TARP is activated to engage the risk owner. The process of reviewing the performance of a TSF and determining if it is performing within defined performance envelopes is highlighted yellow in Figure 1.

The risk owner authorises implementation of defensive actions such as ceasing dry stacking at the affected area, even if this impacts production. Additional actions may include checking and cleaning the underdrainage system and converting monitoring bores to water abstraction bores. If these actions do not return the phreatic surface back to within the performance envelope, additional actions outlined in the ERP, including construction activities and consequence mitigation, would then be followed. These actions are considered rectifications (highlighted red in Figure 1).

Several controls adopted to maintain porewater pressures in the structural zone within the performance envelope and the respective I&M are presented in Table 1.

Table 1 Controls and instrumentation and monitoring

Performance envelope	Supporting controls	Instrumentation and/or monitoring
Porewater pressures below maximum phreatic surface		Piezometers
	Tailings are filtered to 20% moisture content	Filter plant instrumentation Visual inspection of placed material Randomised filter cake testing
	Tailings in structural zone are compacted to +/- 3% of standard maximum dry density	Monthly survey and volume review and reconciliation Cone penetration testing
	Structural zone surface is graded in downstream direction (minimum 2%)	Ongoing visual inspection of placed material Monthly survey
	Underdrainage has capacity exceeding the maximum estimated seepage from filtered stack	Visual inspection of underdrainage outlets for seepage flows and water quality Camera inspections through drainage pipes

6 Conclusion

The previous and continuing failures of extensively instrumented and monitored TSFs demonstrate that the current practice in TSF surveillance can be improved to support TSF safety.

Risk-informed surveillance can be achieved through the definition of performance envelopes, describing and defining the intended and expected performance of all elements of a TSF under foreseeable loading conditions. With respect to TSF safety, performance envelopes should be defined for all safety controls. A suitable form of I&M can then be identified and implemented to monitor the performance of the safety controls, directly linking I&M to TSF safety and risk management. Such I&M systems enable timely identification of deleterious conditions that could lead to TSF failure, allowing for early intervention to mitigate the risk of future failures.

This paper presented a framework that can be used to define TSF safety performance envelopes for planned and existing TSFs. This framework is core to the upcoming ANCOLD Tailings Dam Guidelines, which is in draft at the time of writing. This framework also demonstrates how I&M can be defensibly implemented to reduce the risk of TSF failures when established within a wider tailings safety management system.

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