Advanced Monitoring of Tailings Storage Facilities and Dams to Prevent Failure. Illustrated with Case Studies from UK, Africa and South America

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Abstract

Following the publication of the Global International Standard for Tailings Management (GISTM) many different types of monitoring network have been launched for use in the de-risking of Tailings Storage Facilities (TSF). Management of risk depends on using accurate data that is translated into information, then knowledge. Very fast data transmission coupled to real-time bespoke dashboards have become a significant tool for risk reduction. This paper summarises the monitoring networks available and ranks them for effectiveness in preventing failures.

The main finding is that the best monitoring systems include measurement of the factors behind causes of failure, such as measurement of hydraulic pressures and their speed of change both beneath and around TSF's and dam walls. Groundwater monitoring is an important component for risk management. Linkage to cost effectiveness encourages the systems to be installed and contribute to TSF management. Automation reduces human error. Recalculation of Safety Factors is possible and can be frequently updated.

The essential components of TSF risk reduction are discussed and a blueprint for accurate risk management with practical outcomes is presented. Techniques such as real time geo-resistivity profiling are illustrated.

Case studies from Europe (Keilder Water), Africa and South America (El Soldado) are given and the future of TSF monitoring is discussed.

This work will be very useful to TSF managers and all those involved in promoting the safety of TSF's in all types of climates and terrain. Transparency in information sharing and the international dissemination of TSF health to shareholders, stakeholders, communities and insurers can become routine.

Keywords: Tailings storage facilities (TSF), global international standard for tailings management (GISTM), monitoring, risk, pressures, failure

Introduction

Following the tragic failure of the Tailings Storage Facility (TSF) at Vale's Corrego de Feijao mine in Brumadinho in Brazil in 2019 the combined initiatives of the International Council on Mining and Metals (ICMM), the United Nations Environment Programme (UNEP) and the Principles for Responsible Investment (PRI) – collectively the Global Tailings Review – resulted in the publication in August 2020 of the Global Industry Standard on Tailings Management (GISTM), designed to improve TSF management[1] – see Figure 1 on the next page.

The standard lists six topic areas, 15 principles and 77 auditable requirements. The standard provides a framework for safe tailings facility management while affording operators flexibility as to how to best achieve this goal.

Principle 7 concentrates on the need for monitoring. It includes the design, implementation, and operation of monitoring systems to manage risk at all phases of the facility lifecycle including closure.

[1] https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

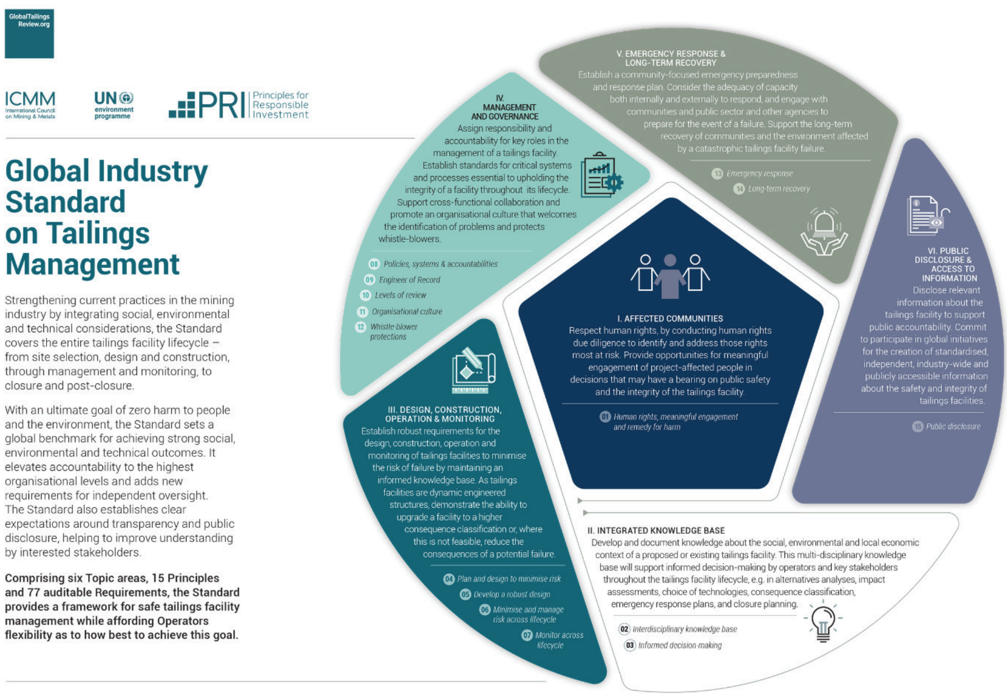

Figure 1 GISTM (https://globaltailingsreview.org/wp-content/uploads/2020/08/GISTM-Summary.png)

Five specific requirements are listed under Principle 7:

1. Design, implement and operate a comprehensive and integrated performance monitoring programme for the tailings facility and its appurtenant structures as part of the Tailings Management Strategy (TMS) and for those aspects of the Environmental and Social Management Systems (ESMS) related to the tailings facility in accordance with the principles of Adaptive Management.
2. Design, implement and operate a comprehensive and integrated engineering monitoring system that is appropriate for verifying design assumptions and for monitoring potential failure modes. Full implementation of the Observational Method shall be adopted for non-brittle failure modes. Brittle failure modes are addressed by conservative design criteria.
3. Establish specific and measurable performance objectives, indicators, criteria, and performance parameters and include them in the design of the monitoring programmes that measure performance throughout the tailings facility lifecycle. Record and evaluate the data at appropriate frequencies. Based on the data obtained, update the monitoring programmes throughout the tailings facility lifecycle to confirm that they remain effective to manage risk.
4. Analyse technical monitoring data at the frequency recommended by the Engineer of record (EOR), and assess the performance of the tailings facility, clearly identifying and presenting evidence on any deviations from the expected performance and any deterioration of the performance over time. Promptly submit evidence to the EOR for review and update the risk assessment and design, if required. Performance outside the expected ranges shall be addressed promptly through Trigger Action Response Plans (TARPs) or critical controls.
5. Report the results of each of the monitoring programmes at the frequency required to meet company and regulatory requirements and, at

__Table 1__ GISTM Principle 7 monitoring implementation for mine water.

Requirement	Implementation		
	Surface water	Groundwater	Climate and hydrology
1 Performance monitoring programme	TSF pond, river and catchment design. Relate to dam breach analysis	Instrument pore water pressure monitoring	Precipitation capture and use of predictive climate models
2 Engineering monitoring	Pumps, pipelines and water balance	Drains, pumps and groundwater balance	Weather stations
3 Establish performance objectives	Limits for flood lines and freeboard	Determine Safety factors and integrate with slope geotechnical design	Determine resilience to extremes and determine risk values
4 Assess performance and link to TARPs	Install TARPs for breaches of dam levels	Design TARPs to intercept and reduce excess pore pressures	Early warning system to predict and manage impact of extreme events
5 Reporting	Dashboard and reviews	Dashboard and numerical modelling	Dashboards and simulations

a minimum, on an annual basis. The Responsible Tailings Facility Engineer (RTFE) and the Engineer of Record (EOR) shall review and approve the technical monitoring reports.

These five requirements emphasise the improvement of monitoring by focussing not only on monitoring critical parameters but also monitoring the effectiveness of the monitoring parameters and equipment used.

Historically, monitoring has emphasised measuring the movement of a TSF but this does not enable management of risk. Measurement of movement is often too late to prevent failure. It is more important to measure the causes behind movement (Morton *et al* 2008 and Morton 2020). Failure in a slope, known as volume deformation, will present (under various pressures and stresses) as three possible scenaria:

1. Compression of water in the pores of the material;
2. Compression of individual particles (sediments, etc.);
3. Re-arrangement of particles, usually to a more compact configuration.

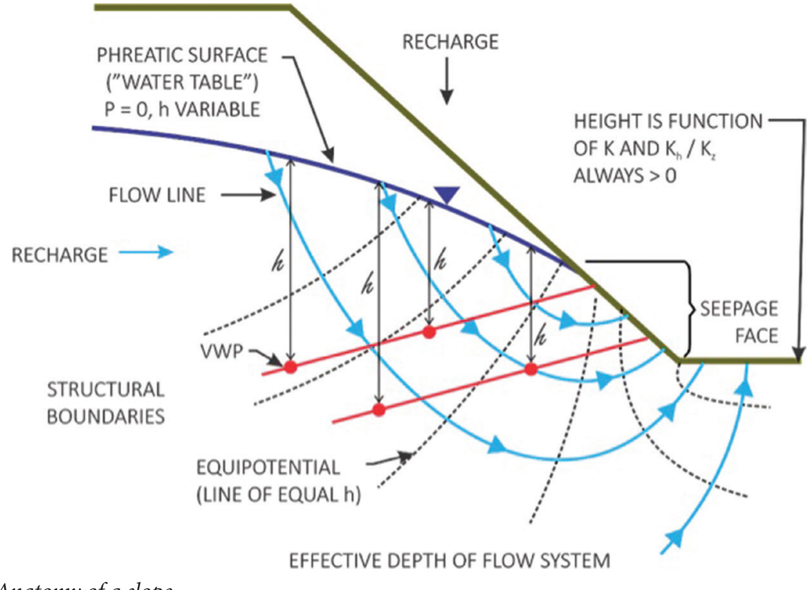

***Figure 2** Anatomy of a slope*

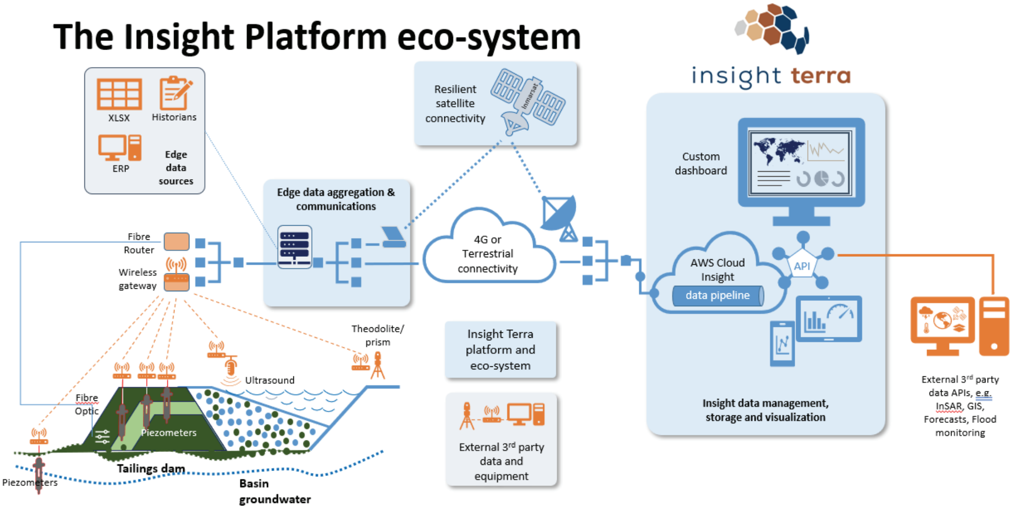

Figure 3 *A monitoring system eco-system*

Once a slope is established the only factor that can be changed to improve the stability of a slope is reducing the weight on, or pressure within, that slope. Figure 2 illustrates the hydraulic anatomy of a slope and the type of installation used to measure the hydraulic pressure gradient.

By draining or pumping the water within the slope the pressures are decreased and the stability of the slope improved. Monitoring systems that not only measure movement of a slope but also measure the causes of failure enable the engineer to better manage the risk and reduce the probability of failure. Figure 3 shows the ideal eco-system for a monitoring network around and on a TSF.

It is also possible to measure the saturation of a slope using geophysical techniques such as geo-resistivity arrays. A permanently installed system called G.Re.T.A. is illustrated

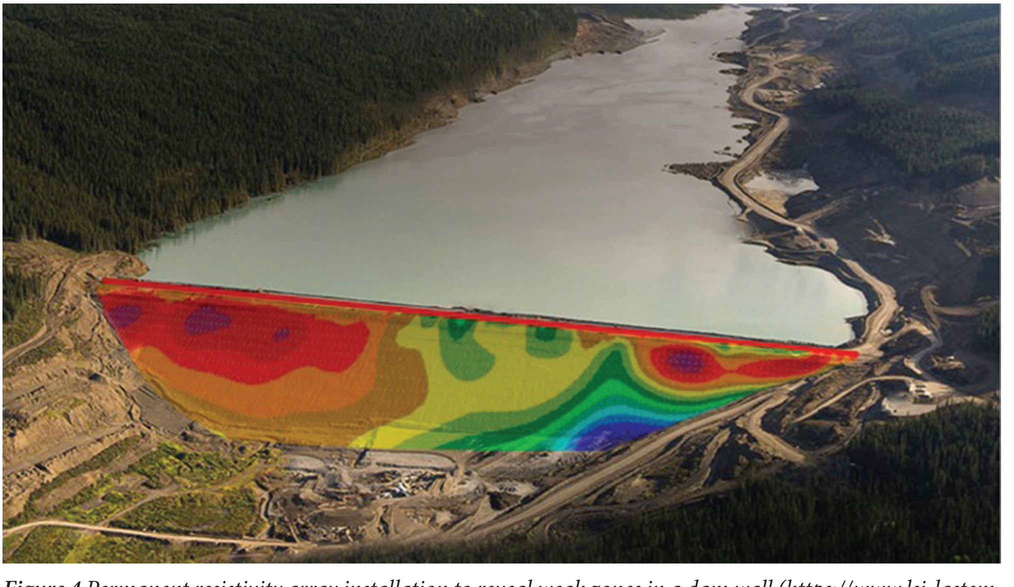

Figure 4 *Permanent resistivity array installation to reveal weak zones in a dam wall (https://www.lsi-lastem.com/products/G.Re.T.A./)*

***Table 2** Methods for TSF Monitoring*

Method	Instrumentation Examples	Advantages and considerations
In-situ – ground based and environmental monitoring	Vibrating wire piezometers, geo-resistivity, inclinometers / shape arrays, load sensors, freeboard, slurry density, weather station – rainfall, evaporation, temperature – downstream boreholes, air quality	Various real-time data from instruments can provide insights into safety states and when integrated with alerts and notifications can provide an early warning of potential failure.
Satellite and aerial monitoring	InSAR satellite, drone imagery, drone – LIDAR, drone surveys, bathymetric surveys	Monitor wide area, however lower frequency of data and post-processing required
Geotechnical modelling	Finite Element Modelling (FEM), seeping modelling, slope stability modelling, Fluid modelling	Identification of potential stability issues before they occur, helps to identify critical risks and preventative measures.

in Figure 4. The red areas are areas of low resistance and therefore highlight weak seepage zones within the TSF of dam wall.

There are many different systems for monitoring the stability of a TSF. Table 2 lists the types and their advantages.

Typically, a combination of the above mentioned methods will be utilised during the phases of the TSF lifecycle. Each of the methods has its advantages depending on the specific requirements of TSF being monitored.

Three case studies are presented:

HDS Case Study

Customer need: to evaluate the effectiveness of its new approach to mine tailings treatment.

Hydraulic Dewatered Stacking (HDS) is part of Anglo American's FutureSmart Mining programme and real-time monitoring of the trial is an essential aspect of this demonstration facility in Chile. The project has multiple objectives:

- To continuously monitor, report on and visualize the facility's health and structural integrity;
- To deliver real time monitoring of the evolving moisture content in the novel dewatered stack approach (HDS); and
- To develop a comprehensive data management platform for the HDS demonstration facility, effectively serving as a proof-of-concept for a broader tailings monitoring solution.

The system comprises a resilient and secure edge- and cloud-based data management and monitoring platform. The edge-based computer node integrates with all nine different sensor types, totalling 108 separate

***Figure 5** El Soldado HDS demonstration facility*

Figure 6 *All weather communications container*

Figure 7 *Keilder Water Dam Wall*

instruments monitoring 500 data monitoring points in, under, around and on the tailings storage facility. All this raw monitoring data is transformed, validated, processed, stored and displayed in the cloud based application, supporting analytics and decision making.

To address the need for reliable communications at the remote location, a satellite communications service – Inmarsat Broadband Global Area Network Machine-2-Machine – is utilised.

An all-weather container houses all the equipment, and is supported by PV solar arrays for totally independent remote operation.

Kielder Water & Dam Monitoring

Customer need: to ensure the continued integrity of the Keilder Water dam wall

Keilder Water is the largest freshwater reservoir in Europe and feeds a catchment area of 23,000 people and 120 businesses. The continued integrity of the dam wall is of utmost importance to these communities and the environment around the reservoir.

The project implemented an IoT-based monitoring system to monitor the stability of the dam wall and the volume of water entering the reservoir from its tributaries. Types of instrumentation included existing standpipe piezometers, biaxial tiltmeters on the dam wall and water level sensors placed in tributaries feeding the reservoir.

An additional challenge was that the whole area around the reservoir has reduced or no cell phone network coverage, and therefore the communications solution supporting the monitoring network needed to consume low power and have long durability, low maintenance and support a very reliable and secure data transfer from sensors to users. Reliable transmission of all the data from the reservoir was made possible by a resilient, all-weather telecoms kiosk that operated 24/7 fully independently off-grid.

Platinum Mine Tailings Facility – South Africa

Customer need: To move from entirely observational monitoring to automated and integrated performance monitoring.

A customer in Africa has implemented a programme of improvement to ensure that its mine tailings facilities all comply with the requirements of the GISTM, published in August 2020. A comprehensive monitoring solution is being rolled out to all its platinum mines in Africa.

The high level solution architecture includes the use of data loggers connected to various sensor types that communicate wirelessly to a central wireless gateway, which then aggregates and transmits the raw data into an AWS cloud-based platform for conversion into engineering data and metrics in a time-series database. The data is processed by the cloud platform in real-time, validated and transformed into insightful metrics and visualisation, ensuring

Figure 8 *Location of tiltmeters on dam wall*

Figure 9 *Tributary sensor locations*

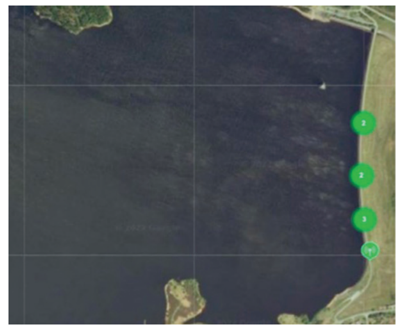

Figure 10 *Water level device*

higher levels of confidence and trust in the interpretation of the data.

Instrumentation was automated in a phased approach, starting with phreatic surface monitoring and additional monitoring uses cases were implemented by priority in an iterative approach over an 18 month period.

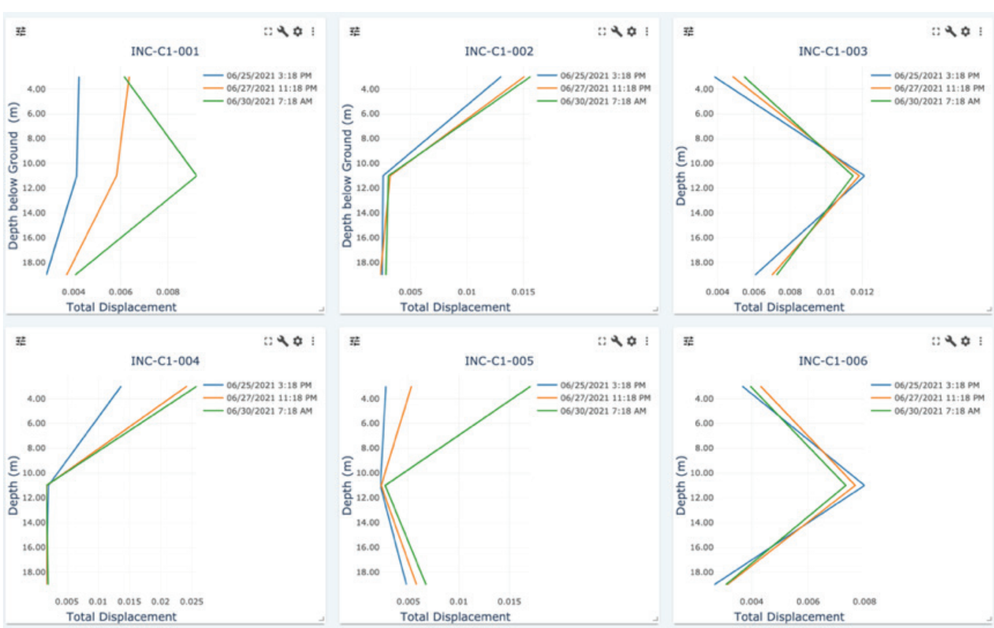

Figure 11 *Inclinometer displacement data visualisation*

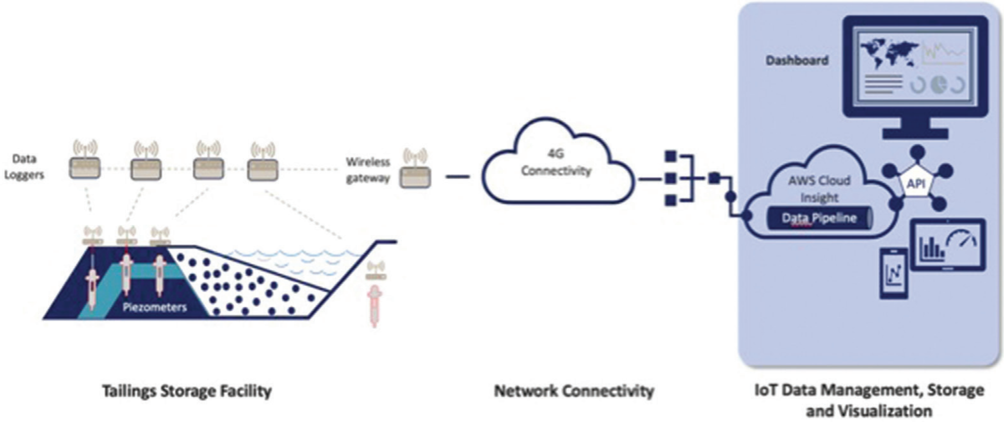

***Figure 12** High level monitoring solution architecture*

Acknowledgements

The authors acknowledge the contribution by Philip Newton of Anglo American plc UK

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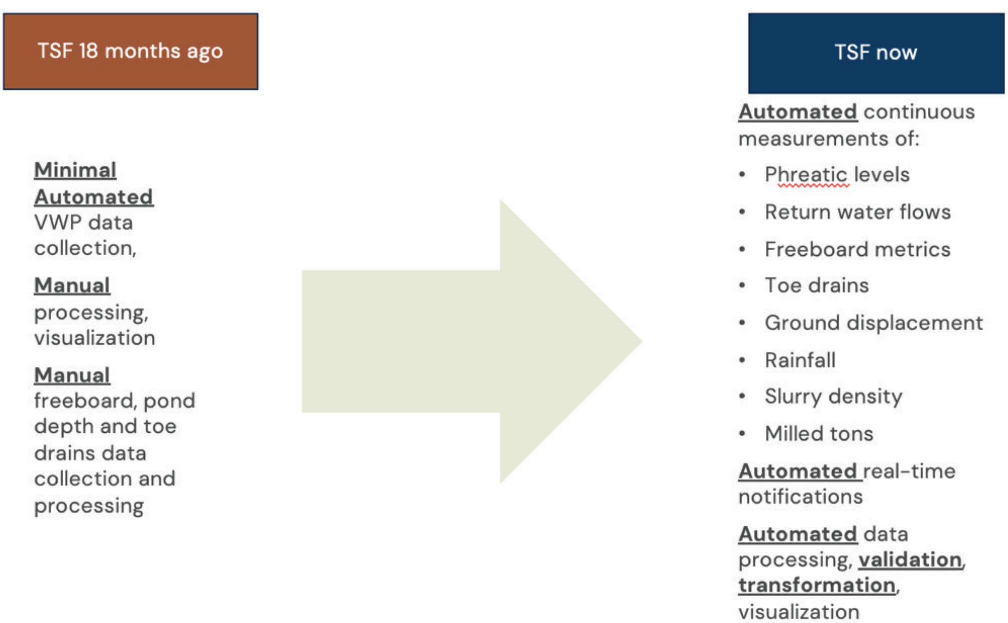

***Figure 13** High level monitoring solution architecture*