A case study for the digital approach to tailings monitoring

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ABSTRACT: In response to catastrophic tailings storage facility (TSF) failures, the Global Industry Standard on Tailings Management (GISTM) was established to promote safer TSF management. This study assesses traditional and digital monitoring approaches for their effectiveness in achieving GISTM compliance. Traditional methods, reliant on infrequent data collection and prone to human error, are compared to digital technologies that enable "real-time" data acquisition via electronic sensors. A case study of a TSF at a mine in Limpopo, South Africa, demonstrates the advantages of integrating cloud-based dashboards and instrumentation. These technologies facilitated the development of Trigger Action Response Plans (TARPs) and enhanced compliance with GISTM principles, such as proactive risk management and informed decision-making. The findings highlight that digital monitoring — alone or combined with traditional methods — provides more accurate, continuous, and reliable data, enabling early failure detection and efficient resource allocation. While traditional methods may suffice for smaller, low-risk TSFs, this study underscores the need for site-specific monitoring strategies to improve safety, operational efficiency, and regulatory compliance.

1 INTRODUCTION

In response to several catastrophic tailings storage facility (TSF) failures in recent decades, such as the Fundão Dam failure in Brazil in 2015 (Carmo et al. 2017) and the Brumadinho disaster in 2019 (Rotta et al. 2020), the Global Industry Standard on Tailings Management (GISTM) was established. The GISTM sets comprehensive standards for tailings management, prioritising safety, environmental protection, and community welfare. As part of these guidelines, principles were incorporated to mandate safe and continuous monitoring of TSFs.

These principles do not outline any specific requirements for effective monitoring systems. However, by using the standards as a guideline and determining the site-specific requirements and proactive management of factors that may affect TSF stability and impact on the environment and communities, advanced TSF management can be achieved.

2 THE NEED FOR MONITORING

Monitoring systems are essential for achieving operational and later closure objectives, which include physical (such as structural), and chemical (such as environmental) stability, as well as managing socio-economic impacts as outlined in the GISTM principles. Routine, systematic, and purposeful data collection is vital for informed decision-making throughout the facility's lifecycle, including during closure planning.

With respect to the GISTM (ICMM 2020), the principles in Table 1 directly relate to monitoring requirements:

Table 1. GISTM Principles for TSF monitoring

Principle	Descriptor
2	Develop and maintain an interdisciplinary knowledge base to support safe tailings management throughout the TSF lifecycle, including closure.
3	Use all elements of the knowledge base - social, environmental, local economic and technical - to inform decisions throughout the TSF lifecycle, including closure.
7	Design, implement and operate monitoring systems to manage risk at all phases of the TSF lifecycle, including closure.
12	Establish a process for reporting and addressing concerns and implement whistleblower protections.
13	Prepare for emergency response to TSF failures.

Adamo (Adamo et al. 2021), emphasize that effective monitoring systems detect risks like extreme weather, seismic activity, geological uncertainties, and variable construction quality across technological generations, enabling timely interventions to prevent failures.

This paper evaluates traditional (manual) TSF monitoring methods and explores integrating digital systems to align with GISTM principles, enhancing oversight. The case study demonstrates a combined approach, assessing GISTM compliance and implementation outcomes to optimize risk mitigation.

3 A TYPICAL MONITORING PROCESS

Cacciuttolo (Cacciuttolo et al. 2024) identified that a monitoring system could be simplified into four basic functions:

i) Acquire data;
ii) Transmit and store the data in a central hub (e.g. a server or data logger);
iii) Process the stored data; and
iv) Visually, graphically, or numerically display that data in an easily accessible format (e.g. a central dashboard).

3.1 Traditional Monitoring

Traditionally, the TSF monitoring process consists of obtaining data using mostly manual methods.

Traditional TSF monitoring has several drawbacks. Freeboard measurement using a surveyor's level is labour-intensive and prone to human error. Standpipe piezometers provide limited data and are dependant on single data points taken manually, only measuring water levels infrequently (without the ability to account for hydrostatic pressures) and do not capture daily fluctuations or pore pressures buildup, leading to limited phreatic level estimates. They can also easily become blocked over time. Seepage monitoring through drain outlets using fixed-volume containers misses flow rate variations, while visual inspections are subjective and labour-intensive. The infrequent nature of these methods delays "real-time" analysis, reducing proactive response capabilities.

The United States Committee on Large Dams (USCOLD) indicated in their report (USCOLD, 1994) that the failures of the 106 incidents reviewed could be related to 8 No. failure mechanisms (as shown in Table 2). These mechanisms each have monitoring parameters as shown by Cacciuttolo (Cacciuttolo et al. 2024) which should be used to develop alert levels.

3.2 GISTM Compliance through Digital Monitoring and Tracking Failure Mechanism Monitoring Parameters

Table 2 shows a comparison of the traditional monitoring approach to the available monitoring technology that could be used in a digital monitoring with respect to the USCOLD failure mechanisms.

Table 2. Failure mechanisms with corresponding traditional monitoring approach and digital monitoring approach.

Failure Mechanism	Traditional Monitoring Approach	Digital Monitoring Approach
1. Slope instability	Freeboard measurement Visual inspection	VWP Inclinometers Fiber optic sensing Extensometers
2. Seepage	Discharge measurement Visual inspection	VWP Flow meters Tiltmeters
3. Foundation	Visual inspection and InSAR	Extensometers Tiltmeters Crack meter Strain gauges
4. Earthquake	Observation of displacement	Seismic gramophone
5. Overtopping	Freeboard measurement	Surveillance system
6. Structural	Visual inspection and InSAR	Tiltmeters Extensometers
7. Internal erosion	Visual inspection	Extensometers VWP
8. Subsidence	Observation of displacement	Seismic gramophone Fiber optic sensing Tiltmeters Extensometers

Ultimately, through the implementation of technology into the monitoring system, the application of digital monitoring techniques assists the TSF owner to achieve their commitment to GISTM compliance and their own TSF management systems.

Figure 1 shows the methods applied through the digital approach and how they are related to the GISTM monitoring principles along with value-enhancement outcomes that was achieved.

Another key advantage of digital monitoring approaches is their ability to leverage advanced technology and remote data tracking to monitor the USCOLD identified failure mechanisms parameters in "real time".

4 CASE STUDY – A COMPARISON OF THE TRADITIONAL AND DIGITAL MONITORING APPROACHES

4.1 The Traditional Approach

To ensure compliance with the GISTM principles, a typical monitoring system consists of obtaining data either through the combination of remote sensing and monthly site visits or purely through monthly site visits alone. The data is generally collected by the site operator and processed by the responsible engineer, and reports are generated to indicate the trends observed for the monitored month.

Some of the typical (although not exhaustive) aspects measured are discussed below with some results from a typical annual monitoring report.

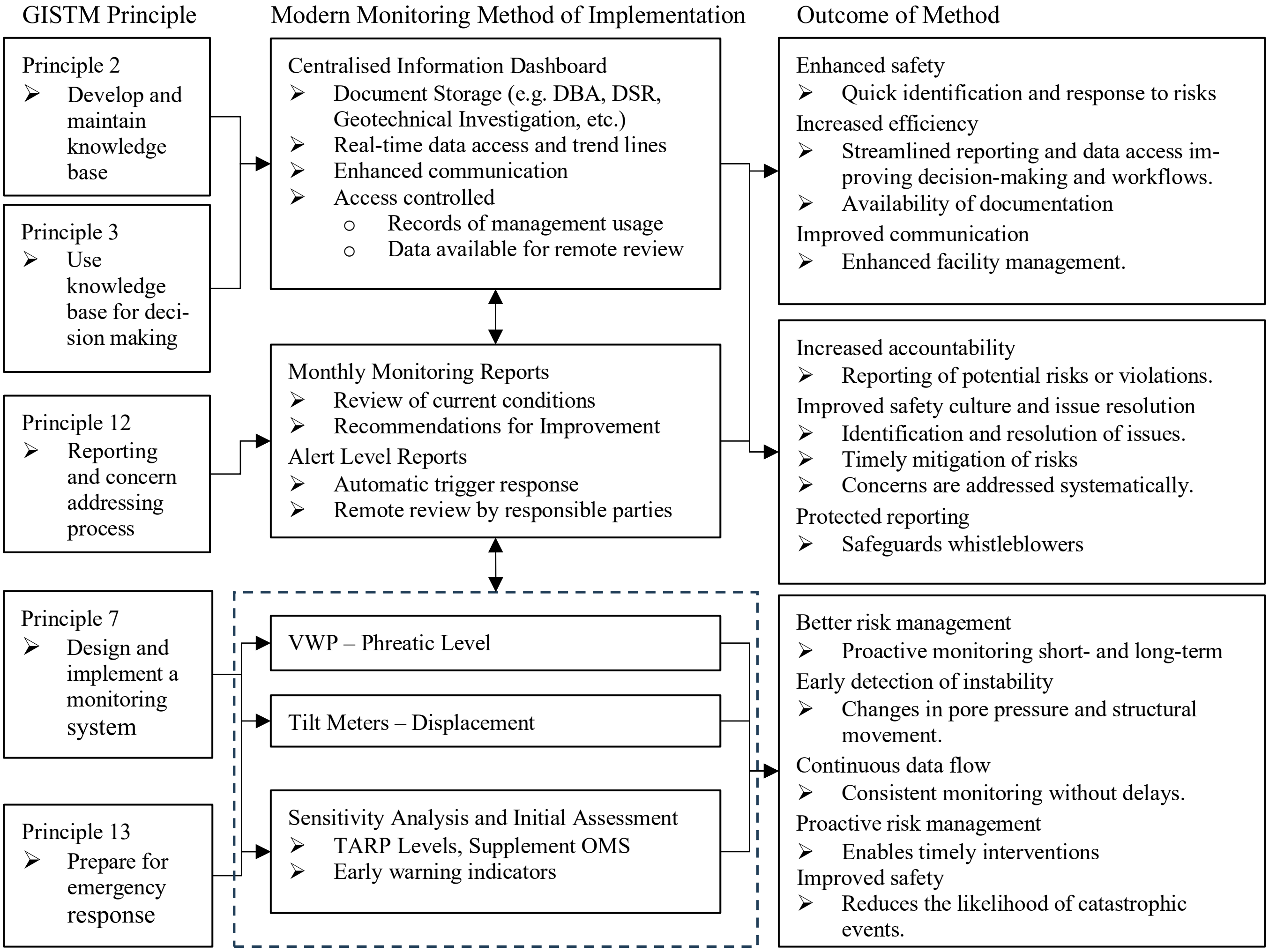

Figure 1. GISTM monitoring principles and case study achievement with related outcomes.

4.1.1 *Phreatic level within the embankment*

Standpipe piezometers installed along TSF embankment walls measure the water depth at specific positions. A dip meter is used to determine the water level in the standpipe, reflecting the phreatic level. Data from multiple piezometers map the phreatic surface, ensuring it stays below critical levels for embankment stability.

4.1.2 *Freeboard measurement*

Using a surveyor's level, the vertical distance between the tailings surface or water level and the crest of the embankment is determined.

Figure 2 shows the annual results of freeboard measurement. The graph shows that the level did not drastically vary. However, it should be noted that due to the measurements only being taken once a month, the results do not indicate the daily variances or drastic changes due to unexpected weather.

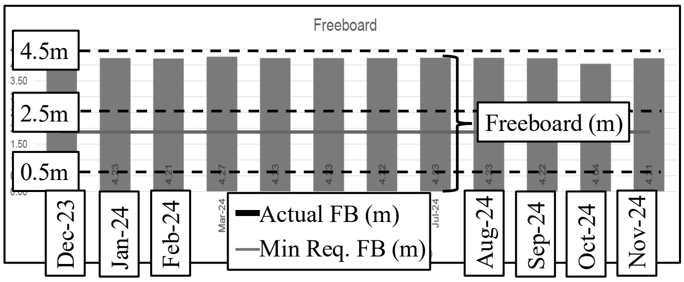

Figure 2. Typical annual monitoring report freeboard measurement results.

4.1.3 *Seepage discharge measurement*

Seepage through a TSF is monitored by measuring underdrain discharge. Fixed-volume containers (such as hand-held bucket) collect seepage water from the drain outlet, and the time to fill the container is recorded with a stopwatch. Flow rate is calculated manually after the recordings are completed. A relationship between the recorded rainfall (Figure 3) and total monthly drain discharge (Figure 4) can be drawn. The graphs represent the coinciding trends well. However, the expected delay of drain flow due to water seepage through the facility – which greatly depends on the permeability of the material – cannot be expressed by singular monthly visits which in effect affects the reliability of the recorded data as it only represents a generalisation.

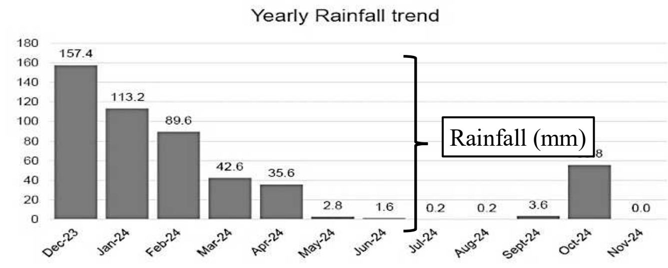

Figure 2. Annual rainfall recorded in the monitoring.

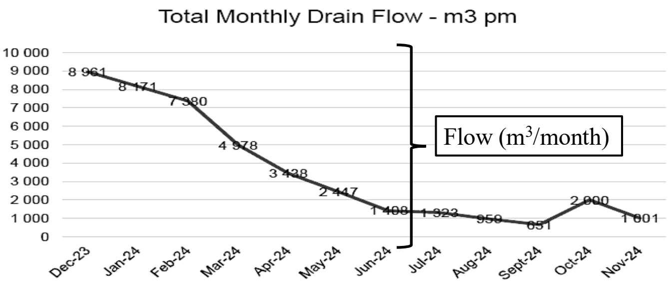

Figure 3. Typical annual monitoring report cumulative monthly drain flow measurement results.

4.2 *The Digital Approach*

A company which was appointed in 2023 to install sensors and monitor multiple TSFs of a mine in Limpopo, South Africa, as part of the mine's TSF management process. The monitoring project commenced after the completion of a geotechnical investigation in which tailings, groundwater and foundation material properties were characterised. Vibrating Wire Piezometers (VWPs) and tilt meters were installed along critical embankment sections of the TSF. A cloud-based dashboard was developed for data collection, storage, interpretation, tracking of trend lines against the predetermined Trigger Action Response Plan (TARP) and providing practical visualisation of the data. The dashboard also contained a document archive, tailored to the owner's TSF management system. Available information was assessed and used in a sensitivity analysis to determine the corresponding and position specific alert levels for each of the VWPs and tilt meters. This information, in conjunction with the seepage analyses, was used to update the TARP.

The case study was completed by reviewing data obtained from the monitored month of January 2025 to assess the digital monitoring approach.

4.2.1 *Weather and Site Conditions During the Monitored Month*

During January 2025, the weather conditions at the case study site were characterized by significant rainfall, with a total precipitation of 234.7 mm recorded throughout the period. The data indicates frequent rainfall events, particularly concentrated in the early to mid-January 2025 period.

Figure 4 indicates the recorded precipitation at the case study site.

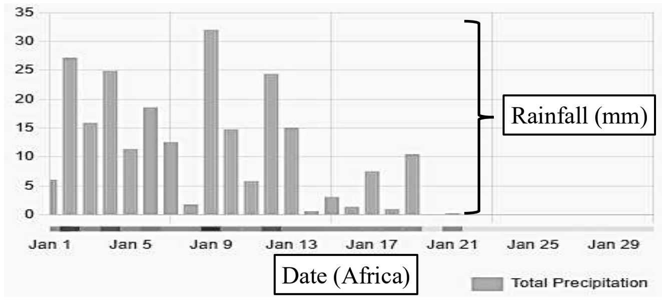

Figure 4. Precipitation for the month of January 2025 at case study site (courtesy Meteostat)

Due to the higher than normal rainfall on the tailings dam, an increase pore pressure was expected. In the case of high precipitation, the TSF may experience face, which could cause slope instability or failure. It also leads to surface erosion, sediment transport, waterlogging, and weakened tailings susceptible to liquefaction (USCOLD 1994).

Monitoring of the TSF during the heavy rainfall period was essential to ensure the facility remains stable.

4.2.2 *Pore Pressure and Phreatic Level Monitoring*

Installing piezometers at various depths along the embankment and inside the paddocks of the TSF, maps the phreatic surface. This enables monitoring of embankment stability by keeping the phreatic level below critical thresholds. The in-situ apparatus accurately measures hydrostatic conditions and porewater pressure.

For the case study site, hydrostatic pressure (converted to water head) at a critical VWP in an operational paddock was monitored during the rainfall period (Section 4.2.1). As shown in Figure 5, pore pressure increased (up to 2.87 m head on 16th of January 2025) until rainfall ceased (~21 January 2025), then gradually dissipated.

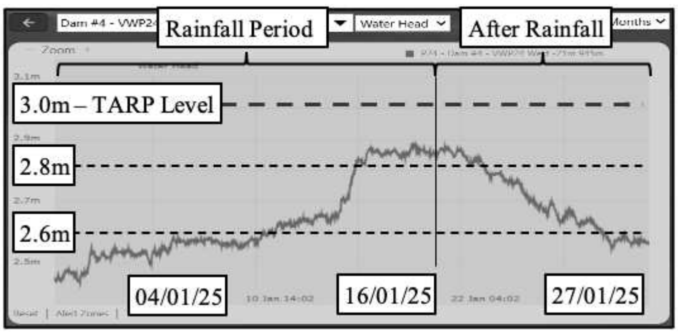

Figure 5. Critical VWP inside a paddock of the operational TSF on the case study site

The pressure head remained within the "Normal Operations (GREEN)" TARP threshold, never exceeding the 3 m "Alert: Investigate (LIGHT BLUE)" level defined in the OMS sensitivity analysis.

4.2.3 *Tilt Meters and Inclinometers for Displacement Monitoring*

Tilt meters and inclinometers measure slope displacement in horizontal directions, detecting angular changes that indicate ground movement and potential instability. Tilt meters offer a quick, "plug and play" advantage, allowing rapid response and tracking of local movements.

In the case study, a tilt meter situated near the VWP in Figure 6, recorded displacement during the rainfall period. Figure 8 shows how the increase in pressure head resulted in displacement of the facility.

A maximum displacement of 9.0 mm in the X (parallel to the embankment) and 14.5 mm in Y (perpendicular to the embankment) axis was measured just after the 16th of January 2025, but it remained within the "Normal Operations (GREEN)" TARP level, below the 20 mm threshold of the "Unusual: Non-Emergency (YELLOW)" level defined in the OMS.

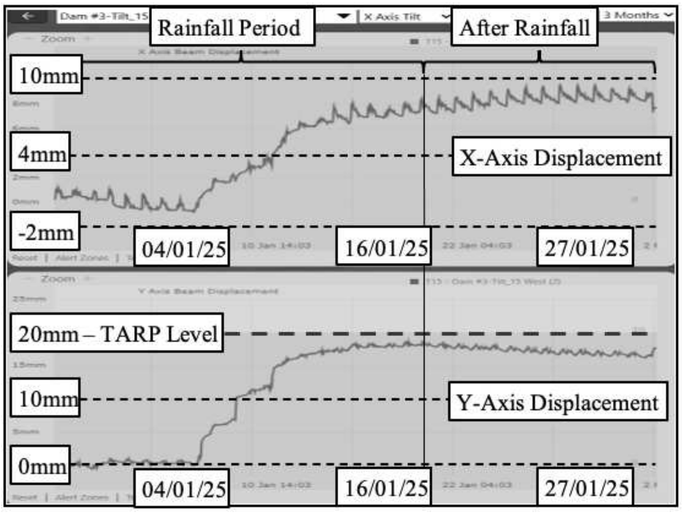

Figure 6. Critical Tilt Meters on embankment in line with critical VWP on the case study site

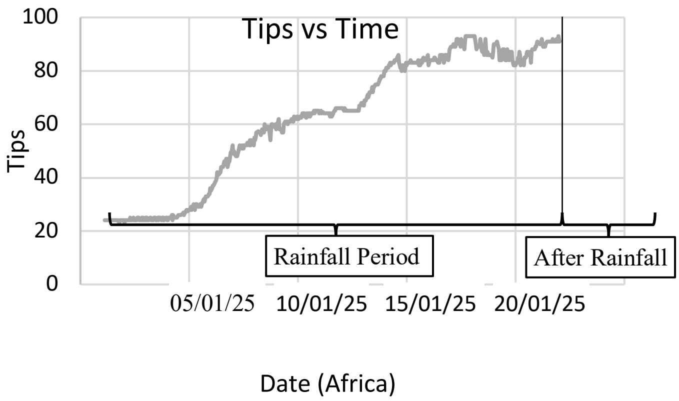

Figure 9. Seepage monitoring experiment results

4.2.4 *Seepage Monitoring Experiment*

The monitoring team recorded seepage by tracking flow through under-drain outlets using a flow meter that correlates bucket tips over time to flow.

Figure 9 represents the results of measuring the discharge from the drains in the form of tips over time resulting in 38.6 l/h for the monitored month.

As seen in Figure 9, with the increase in pressure head (indicated in Figure 7), the seepage through the facility increased as a result of the heavy rainfall period and saturation of the facility.

4.3 Data Utilization

Morton (2021) emphasizes monitoring networks incorporating real-time data, satellite transmission, and customizable dashboards (cloud/on-site storage), enabling tailings engineers to refine designs/safety targets and site teams to manage water levels. Adaptive systems support TSF-specific trend analysis for early failure warnings (Figure 5 and Figure 6).

"Real-time" digital data from monitoring instruments are integrated into a live and cloud-based monitoring system, accessible by authorised staff on their mobile phones or computers from anywhere with internet connectivity. When TARP levels are activated, instantaneous alerts are sent via email and SMS to the relevant management personnel. This ensures rapid response to potential risks by people who need to act. The alert protocol is designed to suit the TARP response requirement as per the mine's TSF management system.

By viewing each of the monitoring parameters in a facility wide network, the digital monitoring system provides a holistic view of the overall stability and conditions of the facility. Pore pressure increase is identified, movement of the facility is noticed, and seepage through the facility can be monitored. By using all the parameter in combination, the system is more effective in determining the facilities condition than the traditional method.

Data is monitored daily and reported monthly. Phreatic levels track drainage/water management efficacy, while displacement data reveals embankment stress or deformation. Analysis identifies seepage-induced erosion, liquefaction potential, or instability, enabling timely risk mitigation.

The Engineer of Record (EOR) updates pre-established stability models with current data. Findings are documented in monthly reports.

An additional benefit of the digital monitoring approach is that the tracked data can then be presented in an automatically generated report which identifies critical sections and data trends. This drastically reduces human error and increases efficiency.

5 CONCLUSIONS AND RECOMMENDATIONS

This study indicated the relevance of monitoring systems in TSF management and safety. The following points of interest were made regarding the two approaches of monitoring:

- The traditional method provided a holistic overview to the condition of the TSF. With respect to the data reviewed, it can be derived from that the TSF investigated was not in a critical condition with minimal freeboard and drain outflows that effectively represented the experienced conditions on site. However, the holistic view could not effectively express instantaneous change. With respect to seepage as measured from the drain flow outlets, due to the method of monitoring, material properties could not effectively be graphically expressed as during a month in which there was high rainfall, the graph showed peaks (as expected). But in the case of a more critical TSF, no indication could be given to the day-to-day conditions and the time dilation due to intermittent data tracking would result in delayed response to a situation which requires immediate input such as liquefaction of basin tailings during a critical storm and seismic event.
- The digital monitoring approach allowed for instantaneous data collection and tracking through the real time monitoring. Remote access enabled the EoR to track the increase in hydrostatic pressure during the rainy season and ensure that the TARP levels were not activated. Reviewing the data allowed mine management to be assured of stability regardless of external factors (such as the heavy rain).
- Additionally, unlike in the traditional monitoring approach, by utilising data from the digital monitoring approach the material properties from laboratory and site investigations can be confirmed. As seen with Figure 5 and Figure 6, there is a delay in time for the build-up of hydrostatic pressure from when the rainfall period begins. This is due to the installation depth of the VWP and the permeability of tailings material. The time for the pressure build-up and installation depth can be used to estimate the material permeability. This can then also be related and compared to the flow rate recorded at the outlet of the underdrains (Figure 8).

Implementation of the traditional or digital approach to monitoring should consider the specific needs and risks of each TSF (as mentioned in Section 3.2). Effective TSF management combines appropriate monitoring tools, thorough documentation, and tailored response strategies.

TSF owners and managers can balance cost, efficiency, and safety while protecting communities and the environment through choosing monitoring systems based on the TSF's hazard classification, size, and operational stage. Electronic sensors are ideal for high-risk or large-scale TSFs, while traditional methods may suffice for low facilities if supported by a well-designed monitoring plan.

Digital methods, using digital instruments provide "real-time", traceable data stored in the cloud and accessible via digital dashboards for easy review anywhere with internet access. These systems deliver near-continuous, accurate data streams and instant alerts, enabling proactive decisions and enhancing the TSF owner's ability to improve management of their facility, getting closer to the vision of "zero harm", in line with GISTM principles.

Budget-constrained or lower-risk facilities may implement a combination of digital tools with conventional methods for cost-effective safety by engaging with experienced practitioners. Low-risk TSFs may rely on monthly inspections and annual trend analysis, provided guidelines ensure traceable data storage. Clarkson & Williams (2019) note that standards like ISO 31000:2009 mandate monitoring strategies, but specifics remain guideline-driven, balancing compliance with practicality.

REFERENCES

Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J. & Knutsson, S. 2021. Monitoring of Tailings Dams and Safety Reviews. *Journal of Earth Sciences and Geotechnical Engineering* 11(1): 249-289.

Cacciuttolo, C., Guzmán, V., Catriñir, P. & Atencio, E. 2024. Sensor Technologies for Safety Monitoring in Mine Tailings Storage Facilities: Solutions in the Industry 4.0 Era. *Minerals* 14(446). DOI: 10.3390/min14050446.

Carmo, F.F., Kamino, L.H.Y., Tobias, R., Campos, A.C., Fonseca do Carmo, F., Silvino, G., Xavier de Castro, K.J.S., Leite Mauro, M., Alonso Rodrigues, N.U., de Souza Miranda, M.P. & Ferreira Pinto, C.E. 2017. Fundão tailings dam failures: The environmental tragedy of the largest technological disaster of Brazilian mining in a global context. *Perspectives in Ecology and Conservation* 15(2): 145–152.

Clarkson, L. & Williams, D. 2019. Critical review of tailings dam monitoring best practice. *International Journal of Mining, Reclamation and Environment*. DOI: 10.1080/17480930.2019.1625172.

ICMM. 2020. Annual Report 2020. *International Council on Mining and Metals*. Available at: https://www.icmm.com/en-gb/annual-reports/2020.

Meteostat. 2025. *Weather in Pemba Airport (FATI0), January 2025*. Available at: https://meteostat.net/en/station/FATI0?t=2025-01-01/2025-01-31 [Accessed: 20 March 2025].

Morton, K.L. 2021. The Use of Accurate Pore Pressure Monitoring for Risk Reduction in Tailings Dams. *Mine Water and the Environment* 40: 42-49. DOI: 10.1007/s10230-020-00736-0.

Rotta, L.H.S., Alcântara, E., Park, E., Negri, R.G., Lin, Y.N., Bernardo, N., Mendes, T.S.G. & Souza Filho, C.R. 2020. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster

in Brazil. *International Journal of Applied Earth Observation and Geoinformation* 90: 102119.
United States Committee on Large Dams (USCOLD). 1994. *Tailings Dam Incidents*. Denver: USCOLD.