Review of modern recommendations for monitoring of tailings storage facilities

Vincent Le Borgne, Ali Siamaki & Adam Dulmage
GKM Consultants, Sainte-Julie, Québec, Canada

1. Canada has a long and rich mining history that has helped shape its growth and identity. This history has unfortunately also led to a legacy of at-risk tailings storage facilities (TSF). Despite constantly improving methods, there are still concerns about TSF management at all steps of a mine's life cycle, from planning to long-term closure. The International Council on Mining and Metals (ICMM) recently released a set of guidelines intended to provide engineers with a framework for TSF management best practices, in line with engineering best practices in related fields such as hydroelectrical power. This extensive document however only devotes a few pages to monitoring, which ought to be thought of a critical part of any TSF management plan. Monitoring is often a low priority for mine operators who perform it without a solid understanding of the science and best practices. However, a properly designed monitoring plan from the outset can help maintain the TSF for decades by providing current and historical data on the structure's behaviour. In this paper, we intend to expand on the ICMM's recommendations for monitoring by providing specific examples from mining projects across Canada. Examples will be drawn from various mines that the authors have worked with to establish comprehensive monitoring plans. We will show that each step of the monitoring plan should be considered carefully. These steps include, but are not limited to: establishing the what, why and where of each instrument, putting together methods for analysis and quality control, the expected range of measurement and threshold for each instrument, how this data links back to the design assumptions and the creation of a "chain of command" should any instrument report data that is out of range. This paper will also provide avenues for pushing the "monitoring" part of best practices beyond simply monitoring to demonstrate why and how it should be integrated into larger internet of things (IoT) and big data practices.

INTRODUCTION

Mines produce large amounts of waste, much more than they produce economic minerals. The waste is typically put in tailings storage facilities (TSF), in which various sizes of ground rock, chemical residue and process water are combined in structures that should be safe and stable over decades. Worldwide, it is estimated that the mining industry produces 14 billion tonnes of tailings annually (Adiansyah *et al.* 2015). TSF can be of a scale similar to hydroelectricity reservoirs, making them collectively some of the world's largest engineering structures. Geotechnical, mining and civil engineers work together to establish strategies that minimize hazard, both to protect a mine's assets and the general public.

Despite mine operators' best intentions, there are several notable examples of TSF failures. The most commonly cited case is the collapse of a dam at an iron ore mine in Brumandinho, Brazil, in which at least 230 (Nogueira 2019) people died, and large areas of agricultural lands were destroyed. This came only four years after the failure of the Bento Rodrigues tailings dam in the area of Brazil (Segura *et al.* 2016). Another major failure occurred at the Philex Padcal mine in the Philippines, in which there were no reported casualties, but significant discharge of solids and pollution from heavy metals (The Catholic Bishops Conference of the Philippines 2012). In Canada, the failure of the mount Polley mine TSF led to a four-square-kilometer tailings ponds draining into Quesnel Lake and the surrounding areas. The mine is now in care and remediation status following a multi-year remediation process (Mining data online 2022).

In the past 50 years, 63 major tailings dam failures have been reported, with the frequency of major events increasing in the past 30 years (Liu et al. 2015). In recent years, it has been reported that 5 to 6 tailings failure occur annually. Several factors could be behind this apparent increase in TSF failures: increased number of facilities worldwide, better reporting, larger facilities, climate change or aging facilities. While there is no public mandatory inventory of TSF and their failures, studies based on publicly available data have largely focused on the mechanisms of dam failures and the design and engineering choices that led to said failures. These studies however often do not have enough data to place these failures in a larger framework that encompasses elements such as management practices, long-term documentation, communications between team and public relations. (Owen at al. 2020)

In order to address these concerns and to increase public trust in TSF, the International Council on Mining and Metals (ICMM) released in 2020 the Global Industry Standard on Tailings Management (GIS, ICMM 2020) and in 2021 the Tailings Management Good Practice Guide (GPG, ICMM 2021). The GIS has a stated goal of enhancing key elements of management and governance needed to maintain TSFs and lower the risk of catastrophic failures. The key elements are: accountability, responsibility and competency, planning and resourcing, risk management, change management, emergency preparedness and response, and review and assurance. As a complement, the GPG gives more direct indications as to how to fulfill the requirements laid out in the GIS.

In this paper, we intend to focus specifically on the "monitoring" of TSFs as described in the GPG. Even though the GPG fleshes out the surveillance requirements of the GIS, it doesn't go into the specifics that are required from engineers and mine operators to properly deploy such a monitoring system. We will show how the monitoring plan should be expanded to include information such as the specifications of the logger used or the structure of databases in order to provide long-term reliability. We will draw from experience with various mines in Canada that have deployed monitoring plans in TSFs, from very basic manually surveyed pressure transducers to fully integrated networks of smart instruments and remote sensing technologies.

THE OPERATION, MAINTENANCE AND SURVEILLANCE MANUAL

The core of TSF monitoring as described in the GPG is the so-called Operation, Maintenance and Surveillance manual (OMS.) The OMS manual acts as the central repository for all things related to OMS activities. As described in the GPG, it should be in line with the performance objectives and risk management plans of the of any given TSF. It should include detailed plans that pertain to the actions to be taken should the TSF performance be outside of specifications, including a description and plan of actions for emergency situations.

According to the GPG, the OMS manual should be site-specific, define roles and responsibilities for individuals and teams, be integrated with sites procedures, be written by engineers with direct knowledge of the TSF, be written for people who actually conduct maintenance of the TSF and be constantly reviewed and improved as needed. The manual is a living document that should undergo frequent revisions and have input as needed from every team involved with the TSF. Operations includes everything pertaining to how the tailings are deposited, construction, water management, reclamation during the operations, closure and post closure phases. Maintenance pertains to maintenance of the structures (e.g., dams), electrical and pumping systems. It should account for preventative, predictive and corrective maintenance.

Surveillance

Historically, many mine operators have built their surveillance systems in a completely ad hoc way without an OMS manual or equivalent document in place. A large mine in Alaska asked us in 2016 to help them organize instruments and monitoring that had been ongoing since the 1980s. Due to poor documentation, staff turnover and evolving practices, most of their instruments and data had become deprecated over time.

One unfortunately common occurrence is that initial readings and calibration factors were lost. While they could still get analog readings from the instruments, the on-site staff had no way of processing them into engineering units. Installing new instruments would have generated new data to work from, but without continuity from previous measurements. Implementing an OMS manual as per the GPG could help avoid many of these pitfalls.

As per the recommendations of the GPG, the OMS should also cover post closure and reclamation projects, including its surveillance program. In several regions, such as Quebec (Mining Act 2022) and Alberta (Alberta Energy Regulator 2022) more stringent environmental laws have forced mine operators to ensure that land could be re-used after a mine closure if possible and that its tailings would be safely contained. We were asked to add monitoring to the TSF of a mine that had closed in the 1980s in southern Quebec. The production and distribution of an OMS manual for this mine would have provided insight into the assumptions and building practices of the TSF. We therefore had minimal information to design an instrumented system to provide some insight to the stability of the structure and if it was leaching contaminants into the water. However, since the design and expected boundaries were not documented in an OMS manual or at all, the government agency’s engineers had to use best guesses as to what to expect, how to select instruments and how to collect data from them. Instruments such as soil moisture sensors, piezometers, matric pressure sensors and thermistors were commissioned in an investigative first phase. The results will be used to design a new and thorough surveillance plan. Figure 1 displays the state of the ground when the monitoring project started, a typical data logger and instruments installed at several depths in the TSF.

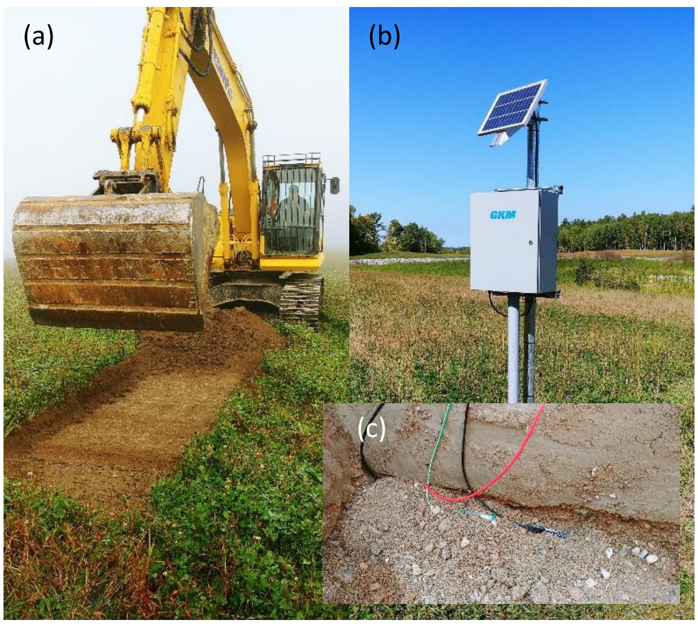

Figure 1 Example instrumentation of a post-closure TSFs (a) Example view of the ground surface in the present day. (b) Typical data logger system (c) Instruments: Dissolved oxygen sensor, temperature sensor, soil moisture sensor and matric tension sensor.

Site observations and inspections

The surveillance section of an OMS manual is split in two components in the GPG: site observations and inspections, and instrument monitoring. For site observations the OMS manual should describe how to document observations and how to report them to the people whose actions might be required. Observations are often done in a more ad hoc way, separate from inspections proper. Therefore, not only should the OMS manual contain the previously mentioned points but a mining site should also instill a culture that makes people care enough to conduct observations as they perform their scheduled tasks and for people in charge of the TSF to take into account these observations. A typical situation would be a rig operator noticing sections of a road undergoing apparent washing out: he should be able to report this information and assured that this report will trigger actions.

Inspections are comparatively structured activities that can be conducted on a schedule or triggered under certain conditions. The scope and object of inspections should be detailed, as well as their frequency, reporting requirements, and processes to document and report on inspections. From a purely technical point of view, inspections have evolved to supplement direct observations with new technologies, including drone inspections, photogrammetry and satellite imagery. Some methods somewhat blur the line between inspections and instrumented monitoring such as INSAR and ground-based radars. Both methods measure long-term deformation of surfaces that could otherwise have been detected by using photogrammetry, GPS or surveying. It is critical that important that these measurements be documented as parts of inspections, but also correlated with instrumented monitoring to produce a thorough understanding of the TSF structures.

Instruments monitoring

While the GPG discusses that instruments monitoring should be conducted, it doesn't discuss the methods. Delving in the intricacies of each technology is beyond the scope of the GPG but there is still room for discussion as to how to structure instruments monitoring and how to integrate it into an OMS manual.

As per the GPG, the OMS manual should describe the parameters to be monitored, the acquisition period for each instrument, the instruments required, who is responsible for the data acquisition, locations of instruments, methods for data acquisition, processes for documenting measurements, quality management and roles, and responsibilities.

It has been a long-standing adage in the geotechnical monitoring community (Dunnicliff 1993) that instruments should have an intent behind them. This has been a good practice for decades as it forces engineers to make choices based on proper understanding and modeling of the structures and puts a stop to a one-size-fits-all approach. It also has proven to be a good cost-control measure, as no more instruments than needed are installed. One of the pitfalls of putting instruments in without a proper plan is to generate too much data that will fall to the wayside or will raise more questions than it answers.

The OPG states that the "methods for data acquisition" should be defined but this is the phrase that requires the most interpretation and that can be expanded upon the most. This requirement is at the crossroads of technology and culture; technological choices affect the organization and organizational choices affect technological choices. We propose to break down the "methods for data acquisition" in four levels, ranging from manual collection of individual instruments to fully integrated internet of things (IoT) systems.

Manual collection of data.

The manual collection of instrument readings is used for background instruments whose readings are not immediately critical to operations or safety. Examples include water level probes and sampling for laboratory control of water quality. This remains a method suitable for large, active and stable sites. The authors have had the opportunity to work with a large oil-sands mine in Canada that maintains and reads thousands of boreholes with manual water level probes and inclinometer probes despite commonly available options for automation. This method generates high of overhead costs per reading and sparse readings, but it can be the most optimal approach depending on the goals laid out in the OMS manual.

Moreover, an oft-neglected advantage of manual collection is that workers can conduct observations and inspections when they are doing their rounds.

The most prominent drawback of manual collection is the lack of traceability of the data and poor practices for data storage. In a typical scenario, a worker writes down the reading in their notebook, put it in a spreadsheet the next day and maybe an engineer will look at the data at an unknown point in the future. Furthermore, as will be discussed in the context of automated systems, the methods surrounding data storage, retention and quality control should be outlined in the OMS manual. This is sometimes overlooked in legacy manual collection-based monitoring plans for older sites.

Data loggers

Standalone data loggers collect data at a set frequency, from which a worker retrieves readings as needed. These systems are usually simple to use and are battery-powered. The main advantage over manual readings is that they acquire readings between rounds; if an unexpected event occurred, this data can be referred to and analyzed as needed. For instance, manually collecting data from manual instruments once a month could miss the effects of large thunderstorms. Data loggers provide more information between rounds to track transitory events.

Telemetry-enabled loggers

Data loggers collect readings from instruments and transmit them remotely so that workers and engineers can have access to them in real-time. Over the past twenty years, advances in microchips and battery technology have made radio-enabled logger an accessible technology to be deployed on TSF around the world. Real-time data can be used to generate reports and analyses that provide direct feedback for operations, environment and security as outlined in the OMS manual. For instance, water levels in a reservoir can be tracked in tandem with pumping rates. It also helps Operations to work closer to the limits of the design assumptions as they can be checked regularly and do not rely on infrequent or unreliable manual data collection. Mines across Canada have begun deploying this method based on various types of logger hardware since the 1990s but there has been exponential growth since 2010. We have installed systems considered to be experimental starting in 2008 where only a few sensors were fully automated and were connected to bulky antennas, loggers and battery packs. In comparison, we now routinely automate TSFs with hundreds of piezometers and other instruments as the hardware has seen large decreases in costs and increases in reliability.

Fully integrated/IoT

The "methods for data acquisition" are currently moving beyond telemetry-enabled loggers and pushing into IoT. In IoT systems, instruments are connected in systems that automate every step from data acquisition to graphing and alerting. Figure 1 shows the nesting structure of the previously described methods, where each expands upon the previous. It can be seen that, given a modular enough design, systems can be modified to integrate more and

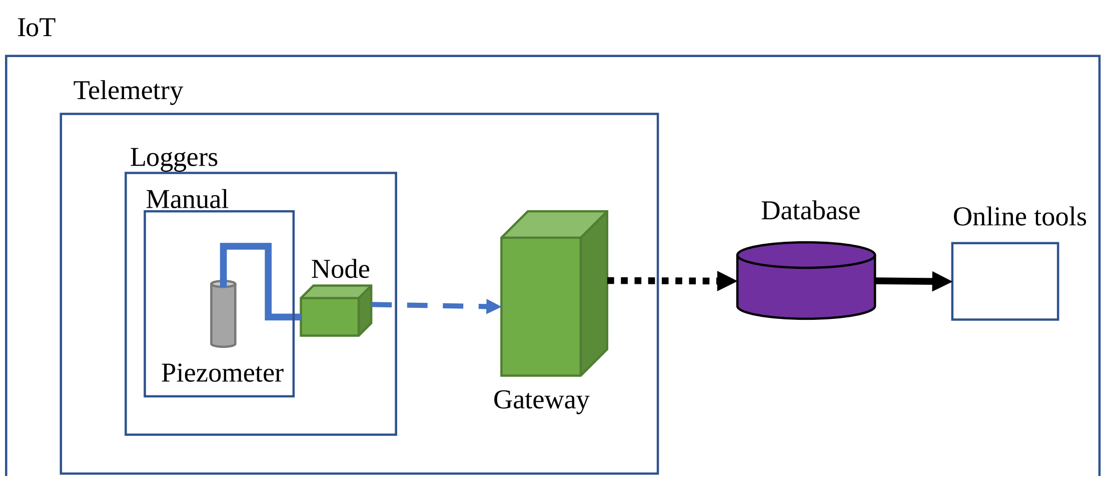

Figure 2 Nesting structure relating the various method of data collection

more automation.

IoT systems can be broken down in several discrete “layers” (Table 1) that more or less map out to the structure outlined in Figure 2. The instrument layer comprises the instruments themselves and related installations, such as piezometers, in-place inclinometers. In many cases, data from the instruments can be collected manually. Instruments are often installed in the ground and as such cannot have any type of telemetry built-in to them due to the physical constraints of the soil blocking any kind of RF communications. In many cases, it is possible to retrofit existing instruments with IoT enabled loggers, further underscoring the divide between the instrument and the node layers. The node layer usually comprises a data logger, an RF module and a power source. The edge device connects the nodes to a local network or to the internet. In other industries, the instrument, node and edge layers are all rolled up into one. For instance, personnel locator emitter contains all of the aforementioned functionalities in a single portative device. In TSFs, however, the lack of availability of power and network connectivity restricts the deployment of distributed connectivity: connection to WiFi, cellular or other types of networks, requires too much power to be powered cost-effectively with a solar panel. Additionally, it is often not possible to deploy power or data lines safely in TSFs as opposed to a factory floor where cabling can be deployed safely and quickly. The management layer is a software layer that assists in the data and inventory management of the instruments and nodes. The application layer is where all data is aggregated and used for monitoring, modeling and more. While in most systems the layers are well-defined, the exact limit separating them can be blurred. Individual nodes can contain an edge device or contain some level of management tools allowing for data quality control before outputting the data on the network.

Table 1 Table detailing examples of items part of each of the 5 layers of an IoT system for TSF

***2.** Instrument*	***3.** Node*	***4.** Edge Device*	***5.** Management*	***6.** Application*
Piezometers	Data logger	Cellular	Instrument inventory	Graphing
Total station	Radio module	Satellite	Data archiving	Automated reports
LIDAR		Gateway	Security	Data analysis
Inclinometers		Distributed gateways	Traceability	Specialized tools

The most common use cases collect data from tens or hundreds of piezometers around TSFs automatically at regular intervals, typically every 1 hour or every 6 hours. These systems can however be expanded with other instrument types and be integrated into other parts of the OMS manual.

The following description should highlight the complexity of these systems and the importance of properly documenting every single item in the OMS manual. At a gold mine in Quebec, we deployed automated monitoring and reporting of vibration data following blasting and seismic events since 2018, using a combination of off-the-shelf and custom software and hardware. In this example, a geophone is read by a vibration monitor, which is in turn connected to a cellular modem. The cellular modem requires a significant amount of power and cannot be powered through batteries alone: a custom solar power system was designed for it. The cellular modem transmits its data to our servers, where custom-made software processes the data, generate reports and makes the readings available online. A sound level-monitor was also commissioned in the same time period. Its built-in cellular modem transfers data to the servers over FTP (file transfer protocol) where the data is manually analyzed by specialists. On the same project, vibrating wire piezometers are read by LoRa-enabled enabled loggers (a low-power, long range radio protocol commonly used in IoT) who transmit their readings to a gateway. The gateway pushes readings in a text file format over FTP to our servers over the internet. The servers contain custom-made software that automatically processes and plots data. In addition to the standard TSF monitoring of piezometers, we have designed an instrument that detects leaks from a groundwater pipe. Leaks are reported through LoRa-enabled loggers to a gateway. In this instance, the gateway is not connected to the internet and the data is processed by mine site's automation software through Modbus/TCP. The software triggers real-time alerts for Operations and Maintenance to take immediate action should any leak be detected. This greatly increases the safety of OMS and helps the mine operator show government agencies that they are controlling the risks related to the release of contaminated waters. A multi-disciplinary team had to come together to design a completely new system that touches upon every single section of the OMS manual as described by the GPG. Figure 3 showcases the various architectures used in this specific project. Each measurement chain is unique and should be documented as such because, as figure 3 shows, each link is different depending on sensor type, connectivity type, visualization method and more. Figure 4 shows pictures for each of these cases. Figure 4 (a) shows the vibration monitor connected to the cellular modem. The geophone is not shown. Figure 4 (b) shows the LoRa logger attached to a pooling section of the protective pipe. It is able to transmit lead detections within minutes of it occurring. Figure 4 (c) shows a typical enclosure with the logger for a piezometer installation near the edge of a TSF.

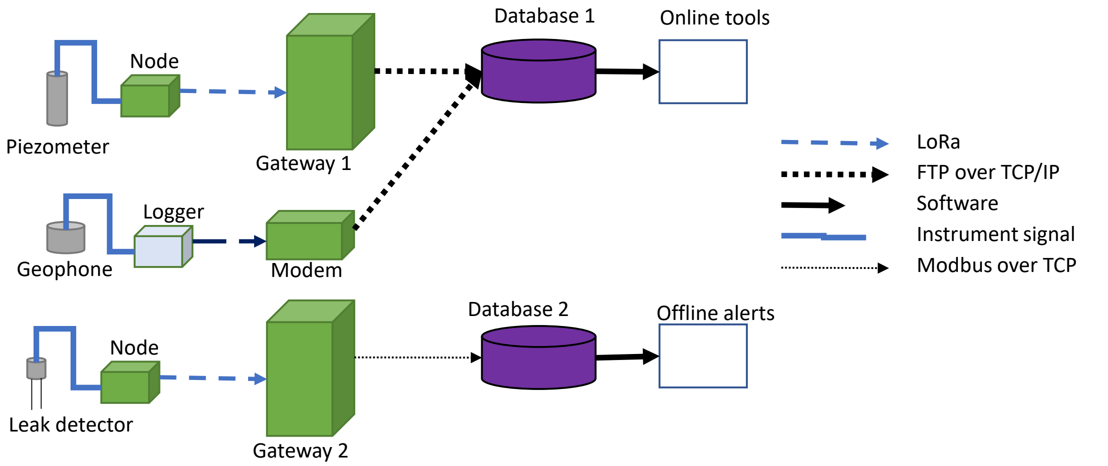

Figure 3 Comparison of the architectures of three separate IoT schemes used on a single gold mine's TSF

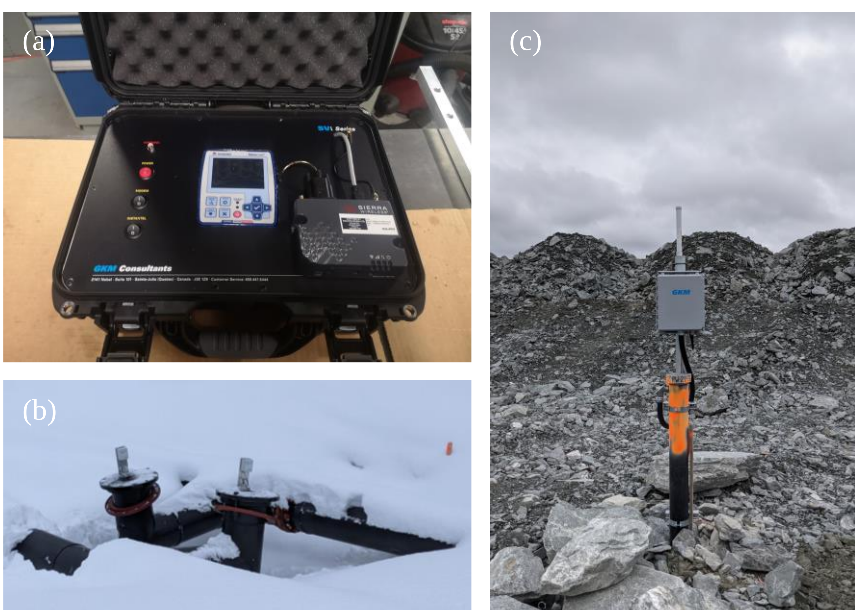

Figure 4 (a) Vibration monitor (center) connected to a cellular modem. Sensor not shown. (b) Leak detection system connected to a LoRa-enabled logger. (c) LoRa-enabled logger for piezometers

The description given in the example above shows that there are a number of details to understand and deploy simultaneously for a successful monitoring plan.   To address this, the following is a non-exhaustive enumeration of items that should be included in an OMS manual.

Type of output of the instruments (vibrating wire, electric, digital, etc.)

-All information regarding the data loggers, including design documents, specification sheets and power requirements.

-Information regarding how the data will be transmitted to a collection point and how data is retrieved from it.

-Information about the protocols and structure of the database where data is stored.

-Methods to access the data in the database.

-Design and specification of the software used to process data and generate reports and alerts.

-A chain of command and responsibilities as to how to distribute and manager real-time alerts.

-A chain of command and responsibilities regarding data integrity, network security, backups and other associated function to guarantee long-term security and traceability

Failure to document any one step as shown in Figure 3 may lead to loss of critical data, years or decades down the road. High-quality documentation has allowed other industries in which automation has been at the forefront to successfully transition and adapt to new technologies as they were introduced.

Other fields implementing IoT systems are facing similar issues such as a requirement for better standardization, a requirement for modular hardware and software, backwards compatibility, and accounting for scalability and futureproofing (Talavera et al. 2017, Saini et al. 2020).

Futureproofing of instruments and loggers

The lifespan of an instrumentation monitoring plan can be significantly extended when the aforementioned information is documented. One salient example is that vibrating wire instruments have been used in this industry for decades and in all likelihood, solutions for readings vibrating wire will be around for several more decades. Digital instruments often have standard protocols such as RS-232 and Modbus. However, if the signal type or protocol of each instrument is not properly documented, replacing the data loggers or even designing new models of data loggers might be impossible. Similarly, the data format output of the loggers or the collection point should be properly documented in case it is ever necessary to retrofit writing data into the database or visualization system. The ability to expand the lifetime of instruments is an important ability in the context of dams: it is often difficult or unsafe to install new instruments in dam cores or other structures. The only safe time to put them is during constructions, and the structures are designed to last for the foreseeable future.

Futureproofing of databases

Futureproofing databases can be as important as futureproofing every other part of the “methods for data acquisition”. Databases should be kept simple, well-designed from the start and be built on proven, robust technologies. A well-documented database structure will facilitate transition to new databases when the currently used one becomes obsolete.

The skillsets related to databases and adjacent tools often fall outside that of geotechnical and civil engineers. It is therefore critical to set up multi-disciplinary teams who can each contribute to each of the building blocks of a successful OMS manual. For instance, we have worked on many projects where years’ worth of data was kept in spreadsheet files. They grew to sizes that made them unmanageable and unworkable, and running custom scripts to extract the needed graphs was needlessly long. In all of these cases, the files were set up with the best intentions by the engineers but without the knowledge needed to properly store and manage data over long period of times.

Review

The GPG offers a list of items that should be updated when reviewing the OMS manual for each of operations, maintenance and surveillance. For surveillance, it is specified usage of each instrument should be reviewed and updated as needed. Time and effort should also be allocated to review integration with other parts of the OMS manual and with risk management plans and key performance indicators. The design of the measurement chain, from the instrument type to the software used for visualization should be reviewed to account for

- Changes in instruments and logger technology
- Changes in technology vendors
- Change in data security and management practices
- Future proofing data and data structures for yet-unknown software or standards

CONCLUSION

An increased number of TSF failures and a decrease in public trust has led the ICMM to provide new standards and good practice guides. The GPG, while exhaustive, does not go in-depth for each technical aspect related to TSF management. The ICMM's GPG provides guidelines for engineers and operators to manage their TSF throughout the mine's lifecycle in sustainable and safe ways. A critical component of the OMS manual is the surveillance program, which requires very careful thought from its inception to its long-term maintenance. Site observations and inspections are usually well-understood by practitioners and their integration into an OMS manual should be straightforward. The design and implementation of an instruments monitoring plan with modern IoT methods requires a significant expansion of the instruments monitoring section of the OMS method plan. The specifics of the surveillance plan, specifically the methods of acquisitions, should be highly detailed in the OMS manual, reviewed frequently and used as a basis for future expansions of the surveillance system as needed.

In addition to providing the tools needed for engineers and mine operators manage TSFs, including information pertaining to communication protocols, data structures and databases in the OMS manual lays the groundwork for the introduction of other methods. In the coming years, new methods such as machine learning algorithms and neural networks will require large datasets to be trained on. The rapid development of these methods is somewhat incompatible with the long timespans of TSF. It is impossible to say with certainty what these methods will be able to accomplish in twenty years. What that in mind, it might be relevant to put in instruments that do not have a clear purpose at the moment but whose data could be retrieved from a database to train AI in decades time.

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