The paper was published in the proceedings of the 11th International Symposium on Field Monitoring in Geomechanics and was edited by Dr. Andrew M. Ridley. The symposium was held in London, United Kingdom, 4-7 September 2022.

Tailing storage facilities: closing the loop between observation and action

Cory BOLEN[1], Michael DAVIS[2]

[1]Stantec Consulting Services Inc., Boise, Idaho, United States
[2]Stantec Consulting Services Inc., Salt Lake City, Utah, United States
Corresponding author: Michael Davis (mike.davis2@stantec.com)

Abstract

Tailing storage facilities (TSFs) are complex geotechnical structures and even the best-intentioned engineering and management teams can be buried in information, clouding engineering judgement and stymieing critical risk informed decision making. Field data, coupled with operator institutional knowledge, is critical to the safe management of TSFs, but what can be done when the information is not easily accessible or automated using conventional sensor and telemetry techniques? How can the time between observation and necessary action be minimized for optimal TSF management?

This paper focuses on how a Geographic Information System (GIS) can be leveraged to bridge qualitative field observations with automated sensor data and historical data sets to give decision makers a full, spatially quantified picture of how these critical structures are performing. Dam inspection forms are built based on the fundamental building blocks of potential failure modes and early warning indicators. Smart-form technology is used to guide would-be inspectors through a rigorous inspection process, regardless of their background or experience; this has standardized the process and increased confidence in the collected data. Inspection observations, maintenance items, and photographs are tagged, tracked, and actioned based on priority and resources. Most importantly, this field data is validated through location tracking services and the results are disseminated to a wide group of people, in near real-time, through web-based maps, dashboards, and automated alerts.

We've also increased our confidence in other conventional instrumentation and transformative monitoring techniques such as Interferometric Synthetic Aperture Radar (InSAR) and have been able to incorporate historical information to plan for future needs on these complex structures. Together these technologies and processes provide the necessary tools to monitor and manage TSFs more comprehensively and effectively.

Keywords: GIS, Digital Transformation, Tailings Storage Facility (TSF), Risk Informed Decision Making

1. Introduction

In the opening chapter of John Dunnicliff's textbook *Geotechnical Instrumentation for Monitoring Field Performance* (Dunnicliff, 1988) he writes *"The engineering practice of geotechnical instrumentation involves a marriage between the capabilities of measuring instruments and the capabilities of people."* Today, more than 40 years after this authoritative textbook was published, we are discovering new ways that this sentence applies in the digital revolution of geotechnical monitoring.

We now find ourselves buried in an overload of data and information, clouding engineering judgement and stymieing critical risk informed decision making. Our methods of data management, aggregation, and interrogation struggle to keep up with the plethora of information, and often fail to incorporate important but overlooked data streams – analogue measurements and observations made by the engineer, scientist, or professional.

As we deep dive into monitoring tailings storage facilities (TSFs), we discover that much of the information we need related to the performance of earth structures, monitoring in geomechanics, comes from the most powerful sensor of all – the human. Technological advances in how we use GIS software have facilitated a much more human driven, customizable approach to field data collection. Smart-form technology is being used to guide would-be inspectors through a rigorous inspection process, regardless of their background or experience; this has standardized the process and increased confidence in the collected data. Inspection observations, maintenance items, and photographs are tagged, tracked, and actioned based on priority and resources. Most importantly, this field data is validated through location tracking services and the results are disseminated to a wide group of people, in near real-time, through web-based maps, dashboards, and automated alerts. Digitizing these critical field observations quickly and clearly at the source then aggregating them with other real-time sensor data is integral to comprehensive geotechnical monitoring systems that minimize the time between observation and action.

2. Tailings Storage Facilities and the Engineer of Record

Stantec values the importance of the role of the Engineer of Record (EOR) for TSFs and our professionals who fulfil and support that role. We are retained by clients at sites around the world to provide this critical piece of the TSF safety management framework. The role and associated qualifications of the EOR has been receiving attention by mining companies, regulators, and engineering companies as the demand for EOR services for TSFs has become more prominent in the industry because of continuing TSF failures. New industry guidance such as the Global Industry Standard on Tailings Management (Global Tailings Review, 2020) has also been released which includes the requirement that an EOR firm and individual be appointed in the design and construction of a TSF.

As an EOR, the time between observation and action is critical in making informed decisions to modify tailings placement, construction rates, complete remedial measures to prevent failure, or enact emergency response plans. This requires digitization and aggregation of data such as inspection records that can indicate structural weakness, changing conditions, or potential failure modes as early as possible. In this regard, Geographic Information Systems (GIS) are being used by Stantec's EOR teams to overcome the challenges associated with aggregating digital and analogue data sets. Stantec relies on GIS and geospatial technologies to assemble, integrate, and interrogate spatial data. In particular, the GIS software platform is being utilized to digitally transform how our discipline experts and clients collect, manage, interact, visualize, analyse, share, and report on their data.

3. Common Challenges in Monitoring Tailing Storage Facilities

TSFs are inherently complex. This is because they are built over long periods of time in changing environments, complex regulatory conditions, cyclical, commodity-based economies, and under the guidance and constraints of multiple stakeholders including owner(s), consultant(s), regulatory bodies, and others. Integrating of all the data and information to support monitoring these structures has some significant challenges, including:

- Long periods of time between observation and action – TSFs are often designed, operated, and managed by global teams of experts. When inspection or monitoring is done by paper methods, it can take days or weeks for information to be received, analysed, and understood by all stakeholders.
- Disparate data sets and software platforms – "There's an app for that." This frequently uttered phrase is rampant in performance monitoring today, but no single platform does a great job of integrating all the data. Each sensor, vendor, and organization have their own software platform and some only cater to a specific device or sensor. The single source of truth data management application for all performance monitoring data is still in its infancy.
- Validation of manually collected data and observations is tricky – Verifying that the observations and data were collected at the right location at the right time is impossible without technology. How thoroughly are inspections being done? Are the important structures and locations being given adequate attention? How much time do inspections take and what is an appropriate level of staffing to get the job done properly?
- A box ticking exercise – Routine inspections are often completed to satisfy a regulatory requirement. This approach can become pervasive in organizations when routine inspection and monitoring become activities completed in complacency and lose their efficacy with respect to the dam safety management system.
- Rigid data entry forms and tools – Digital inspection and monitoring systems are often designed by offsite staff that view data collection in a logical way as part of a desktop exercise. This can lead to overly rigid forms and tools that inhibit data entry during field collection. Data entry schemes need to be flexible to incorporate changing field and site conditions that may be unforeseen during the design process.
- Adaptation to digital workflows – "If it isn't broken, don't fix it." We are creatures of comfort and data collection routines that have been used for decades are hard to change, but digital transformation starts with people transformation. Often, existing data collection routines have been designed and refined to

meet very specific requirements and changes to the data collection or reporting can raise questions with regulatory bodies and external stakeholders. There is a pervasive "don't rock the boat" mentality when something is working, even if there are better or more efficient ways of collecting and reporting the data.

4. Leveraging GIS as a Data Integrator

In the current information age, collection of data can be in various forms ranging from in person, on the ground observations to automated instrument readings, desktop reviews, and remotely sensed data. Information sources are almost as varied as the information itself. As a result of the vast amount of information required to effectively inform decisions an information aggregation platform is essential.

We have identified GIS as a core technology and platform that can integrate multiple types and sources of information, as well as provide the added benefit of location intelligence all in a near real-time environment. A GIS-based approach tracks the location, or the 'where' component of the information being collected, which is a critical component of effective geotechnical monitoring. Field-based information is collected directly in a digital format with spatial context that syncs directly to a cloud computing environment. This provides all stakeholders access to critical on the ground information in near real-time.

Supplemental data streams from automated geotechnical sensor systems or publicly available web services (e.g., climate data) are also integrated into the system. Additionally, historical reports, as-built surveys, and aerial or drone imagery can be assigned to spatially explicit assets for future reference. The integration of information sources to a centralized platform provides the necessary and complete picture of the infrastructure being monitored. Complementing the spatial and data management components of a GIS are visualization tools. Inherent to GIS is the ability to analyse data with a spatial lens, resulting in new understandings of structural performance that often go unrealized in more traditional methods of data analysis. Specific visualization tools include interactive web map applications and dashboards that further connect the data and provide centralized access to what would otherwise be an excess of disconnected information. All applications and tools are hosted in a centralized hub-site which serves as a "one stop shop" for all data and analyses.

4.1 Dam Inspection Forms

To support routine and frequent ground-based inspection and monitoring activities, GIS-centric mobile applications are configured to align with a specific site's relevant infrastructure, potential failure modes, early warning indicators and on-site workflows in mind (Figure 1). The forms rely on smart-form technology requiring only the collection of relevant information. Information collected is standardized through a well thought out data management scheme that pairs the technical expert's knowledge with technology. Data validation techniques are employed throughout form designs to further increase data integrity and future usability. Forms are also modelled around how personnel collect the data. Effective form designs ultimately serve as a guide to the person collecting the data of what features to inspect or monitor, what key indicators should be considered, and how to collect useful information regardless of whether the person collecting the information is familiar with TSFs or not.

Supplementing textual and tabular observations, photos are taken directly in the system and tagged with specific attributes and location-based information which allows them to be easily referenced through queries of the online system. Site features of concerns such as seeps or sinkholes can then easily be compared and tracked temporally through dashboards. Photos can be watermarked or annotated to provide further context of the observation being made. Also, observations can be supplemented with digital site sketches or physical mapping of features (points, lines, and polygons) and extents. On the fly calculations and comparison to historical values or thresholds are used to evaluate and automatically trigger notifications to key personnel if a critical safety or structural issue is identified.

Forms can be completed in either an online or offline environment. If working in an offline environment, data collected syncs to the cloud platform once connectivity to a cellular or Wi-Fi network is restored. The near real-time access to the data eliminates unnecessary bottlenecks in the information pipeline and allows for timely independent quality assurance and sign-off. Inspection review and sign-off occurs directly in a sign-off dashboard in the cloud system allowing the reviewer to review, edit, assign and/or flag observations for further review by the EOR. Upon completion, routine inspections can be output to automated reports to meet regulatory reporting requirements.

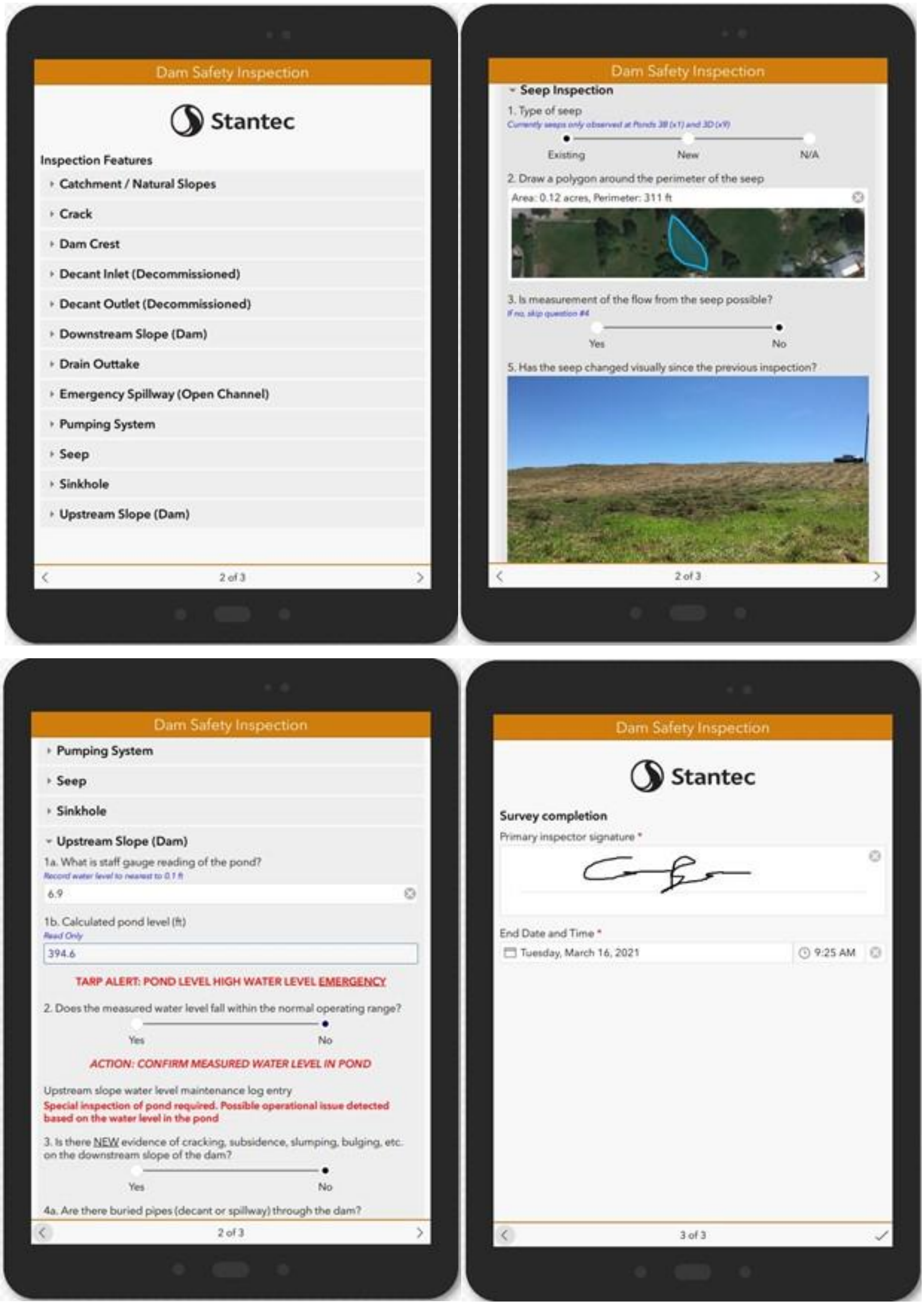

Figure 1: Example GIS-based digital inspection form.

4.2 Maintenance Log Tracking

Maintenance logs are used to identify and track all action items related to repair or continuous improvement of a TSF. Collection of observations relating to repair and maintenance is critical, and so is following up on these identified items to make sure they have been completed. To help close the loop between outstanding and completed action items, tagged observations and the associated photos are routed automatically to a maintenance dashboard where dam safety management personnel or the EOR can review and prioritize the urgency of the action items and the associated mitigation or repair (Figure 2). Once complete, the status of the observation is updated, completion date noted, and additional photos taken to document the repaired conditions. Beyond serving as a maintenance tracking tool, the dashboard allows the ability to digitally track work activities for both budgetary planning and annual regulatory reporting.

Figure 2: Example maintenance dashboard.

4.3 Historical Data

Historical site data serves as an important record of past conditions. An overarching data management system must not only account for the collection, management, and visualization of new data, but also existing historical site data such as aerial photographs. Migrating historical data into the data management system provides access to visual comparison of historical and current information at specific locations of the site (Figure 3).

Figure 3: Example historical aerial image catalogue web application (left 1990, right 2021).

4.4 Instrumentation and Sensor Data

Integrating instrumentation and sensor data with visual observations is necessary for a comprehensive and effective monitoring system in that it offers insight into geotechnical performance that is not readily observable (e.g., groundwater levels). Custom GIS-based applications have been configured to analyse, integrate, and plot both automated and manually read sensor data. In addition, instrumentation and sensor data that is not easily automated (e.g., pneumatic piezometers) can be collected and plotted through the GIS-based applications. Alerts and thresholds can be set on the data entry values which allows for potential data entry errors to be noticed in the field at time of entry. Once the data is synced, readings are then available in an instrument specific analytical dashboard for review and reporting.

4.5 Digitizing and Preserving Institutional Knowledge

While the GIS software serves as a centralized platform for various types of information, the advantages of the system go beyond data management and access. The platform serves as a place for both client and consultant knowledge to come together and form a comprehensive record. Through interactive web maps and dashboards, new questions can be raised, instigating new discussions that may not have previously occurred between stakeholders. Also, simple routine operational workflows such as the adding and removing of weir boards to control water levels can be documented through time. This allows the next individual or organization tasked with the responsibility for the dam safety management systems to be informed of the monitoring methodologies or operational requirements that often go undocumented.

4.6 Integration of InSAR

Interferometric Synthetic Aperture Radar (InSAR) is a technology that helps us understand behaviours in ground deformations over vast areas, through time. Our understanding of this technology and its many applications is rapidly advancing. Typically, processing of InSAR data is provided by third-party vendors which specialize in processing raw radar data from satellites. Using GIS, we've taken InSAR data interpretation to the next level; we have created a GIS workflow to ingest the big data sets of InSAR into an easy-to-use analytical web tool that empowers decision makers to formulate their own interpretations of the data (Figure 4). Data is presented in a heat map with dynamic selection tools allowing the user to focus on a specific area of concern. Temporal data trends are then automatically plotted both by year and by average displacement in the horizontal and vertical directions. Graphs can also then by dynamically focused to a specific time frame of interest. To date, the tool has easily processed up to 500 million data points making the InSAR technology that more powerful in application.

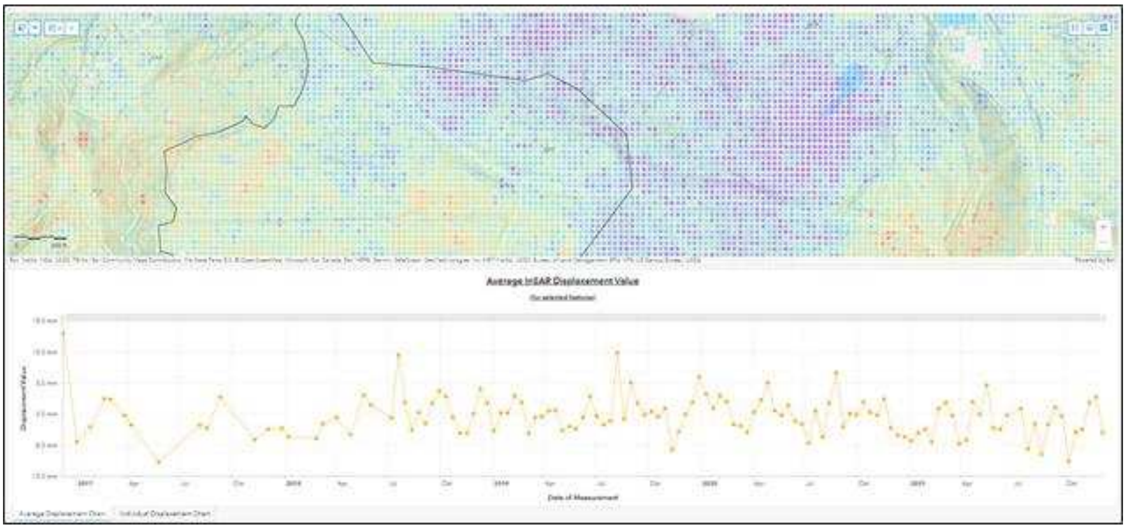

Figure 4: InSAR data viewer.

4.7 Building Resiliency

TSFs have long life cycles that will outlive the careers of those who design, construct, and manage these structures. The GIS-based monitoring systems serve as the living platform to store a complete data record. Data accessibility enhances the quality assurance process and serves as an important trust component between various stakeholder groups.

5. Challenges

Digital transformation can be difficult. Despite the critical nature of all the described components of an effective, comprehensive geotechnical monitoring system, aligning stakeholders and implementing these systems comes with inherent challenges.

- Stakeholder alignment and change management – Achieving and maintaining alignment across multiple stakeholder organizations is critical to the long-term success of data management solutions. Changes in project ownership, attrition, and shuffling of roles and responsibilities can all pose challenges to the implementation of a digitalized monitoring system. The development of a stakeholder registry, regular development meetings and communication, and relevant training can help keep stakeholders aligned, informed, and driving towards common goals.
- Sustaining investment – Data management does not have a finite lifecycle as many other types of engineering projects do. Inspection and monitoring of a TSF can span many decades, technologies, and even industrial revolutions. Securing funding and planning for the ongoing performance monitoring and data management systems is key to meeting stakeholder objectives.
- Information technology (IT), data sharing, and security – Limitations in an owner's tolerance for data sharing pose a significant challenge in implementing technological advancements. Removing barriers to data sharing requires appropriate engagement from field personnel to the executive management level. In anticipation of machine learning applications that require large datasets we need to address Intellectual Property (IP), confidentiality, and information security so that we can all benefit from our broad and collective knowledge.

6. Conclusion

Martin Recke writes that the fourth industrial revolution (Industry 4.0) has marked the beginning of the "Imagination Age" in our civilization (Recke, 2019). We will continue to delegate knowledge work, thinking, and analysis to machines, and creativity and innovation will become the primary creators of economic value. This is the direction we are taking with our digital geotechnical performance monitoring systems.

Mine operators need sophisticated data storage and management systems, and they also need efficient ways to pull and analyse the data for it to be useful in practice (Adams et al, 2021). As data increases, we need sophisticated tools that can run instant analyses to identify critical risks in a timely manner. Further incremental change will still be needed to achieve the vision where geotechnical monitoring information is seamlessly paired with advanced analytics, machine learning, and AI to supplement, enhance, and facilitate this type of holistic geotechnical monitoring approach to TSF management. For now, we see great advantages offered to TSF monitoring and management with the digital tools now available.

It is imperative to digitize and automate as much information as possible to minimize the time between observation and necessary actions. GIS-based tools and applications are the means to providing a full, spatially quantified picture of how TSFs are behaving, as using these systems standardize field data collection which results in increased confidence in the information gathered. These practices and technologies paired with the application of engineering judgement provide a complete and effective means to managing TSFs that will be critical to informing advanced analytical systems of the future.

Acknowledgements

The authors wish to thank the many Stantec clients who believe that digital transformation of inspection and monitoring data has a positive impact on dam safety management systems. In addition, these advancements would not be possible without Stantec's inspired culture of innovation and creativity that continues to support a fundamental shift in how we value performance monitoring data and the digital revolution.

References

Dunnicliff, J. (1988). *Geotechnical Instrumentation for Monitoring Field Performance*

Recke, M. (2019). *Why imagination and creativity are primary value creators.*

Adams, A., Johnson, D., Salimi, K. (2021). Tailings management, meet science fiction. *Global Mining Review*, November/December 2021.

Global Tailings Review (2020). *Global Industry Standard on Tailings Management*.