Lessons Learned from Implementation of an Integrated Data Management System for Tailings Impoundment Dams

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Abstract-- Tailings basins are often large, complex facilities that continuously evolve as impoundment dams are raised to allow for additional tailings storage. The complex and dynamic nature of these facilities requires close monitoring and surveillance to promote safe operations and allow for optimized designs. This often results in large datasets that are difficult to manage, increasing the risk that important information will be missed, misinterpreted, or not received quickly enough. This paper presents a case history in which a tablet computer application and customized database with geographic information system (GIS) interface were developed to compile, synthesize, and interpret large datasets that were previously scattered and difficult to manage. The primary benefit for the facility and engineer of record has been quick access to current information, including instrumentation monitoring and site surveillance data. The ability of both parties to simultaneously review data allows for timely decisions, including those related to changes in site conditions and instrumentation threshold exceedances. With these successes have also come challenges, such as integrating multiple software systems to provide the desired functionality. Recommendations for similar systems are provided based on these experiences.

I. Introduction and Background

The work described in this paper was completed for a confidential tailings storage facility using the Observational Method for impoundment dam design. As part of this work, a large instrumentation monitoring and surveillance program has been implemented, producing significant amounts of data. Previous methods of managing this data were cumbersome and inefficient. As database and computing technology have improved and become more accessible, data management practices at the facility have improved as well. The following describes the successful implementation of an integrated data management system. Recommendations for development of similar systems are provided based on the authors' experiences.

II. Facility Description

The size of the facility, its geology, and the nature of its operation present a wide range of geotechnical challenges for the authors who, along with their colleagues, serve as the facility's engineer of record. The typical geology beneath the facility consists of glacial deposits, including clay till underlain by a pressurized sand aquifer, and bedrock. Additionally, portions of the facility are underlain by muskeg deposits consisting of peat and organic clay. The challenges to dam design and performance presented by the geology have resulted in a sizeable instrumentation system.

As with other tailings storage facilities, impoundment dams are continuously raised to allow for additional tailings storage. Initial dam construction was completed using combinations of downstream and upstream construction methods. The offset upstream construction method is currently being used to raise the impoundment dams, which has resulted in overall dam heights in excess of 100 feet. The offset upstream construction method has many benefits but also presents the challenge of constructing over relatively low-strength fine tailings. The use of offset upstream construction over fine tailings, which uses a staged construction approach, requires an understanding of foundation pore-water pressure conditions and consolidation, which are assessed through piezometer and settlement plate monitoring.

Additionally, the slurry discharge of tailings into the facility causes water to be stored upstream of some of the impoundment dams. The resulting pore-water pressures and phreatic surface through the dam must be carefully monitored to ensure that dam performance criteria are met and that assumptions made during design are valid.

These challenges have warranted the significant investment in the instrumentation monitoring and surveillance program used at the facility, which is further described in the paragraphs that follow.

III. Use of the Observational Method at the Facility

Design based on worst-case conditions is not cost effective, but provides some degree of assurance that the structure will not develop unanticipated defects [1]. The facility described in this paper uses the Observational Method presented by Dr. Ralph Peck [2]. With this method, design is based on geotechnical investigations that provide an understanding of the general nature of the site and identify the most probable conditions. Instrumentation monitoring and observation during construction can then be used to modify the design, as needed. Following construction, the method can be extended through continued monitoring and surveillance during operation.

For the Observational Method to be effective, an investment in construction observation, instrumentation monitoring, and surveillance must be made. For large facilities such as tailings basins, this investment may be significant. The data derived from these activities also requires an investment in data management, as described in this paper. However, there is the potential for significant construction cost savings and risk reduction through proper application of the method.

IV. Instrumentation Monitoring at the Facility

Given its size and the risks inherent to tailings storage, the facility has made a significant investment in instrumentation to promote safe operation. Facility staff also recognize the value instrumentation provides in terms of construction cost savings through application of the Observational Method.

The instrumentation monitoring program at the facility is summarized in Table I. Also included is a short description of the each instrument type's purpose.

TABLE I
Summary of Instrumentation Types at the Facility

Measurement Type	Instrument Type	Approx. No.	Purpose
Water Pressure	Piezometers – Vibrating Wire	250	Monitor pore-water pressures (particularly during construction) and seepage model calibration
	Piezometers – Open Pipe (Screened)	200	Monitor pore-water pressures and perform slug and tracer testing (particularly in a pressurized sand aquifer) and seepage model calibration
	Piezometers – Open Pipe (Fully Screened)		Monitor location of phreatic surface through dam cross-section and seepage model calibration
	Piezometers – Pneumatic	20	Monitor pore-water pressures (instruments are being phased out and replaced with other piezometer types)
Deformation	Settlement Plates	300	Monitor construction-induced settlement and deformation model calibration
	Inclinometers – Traditional and ShapeAccelArray (SAA)	10	Monitor lateral deformation, particularly within muskeg deposits and fine tailings deposits beneath offset upstream construction
	Magnetic Extensometers	20	Monitor vertical deformation of inclinometer casing
	Survey Prisms	40	Monitor surface deformation along dam slopes
Flow	Weir Boxes	20	Monitor flow and changing seepage conditions
	Relief Wells	50	Monitor pressure relief in sand aquifer
System Performance	Flow Meter	2	Monitor relief well system performance and effectiveness
	Water Level Meter	1	

In general, instrumentation monitoring data is collected by field technicians contracted by the facility and provided to the engineer of record for review, assessment, and evaluation. Observations made from the data are reported to the facility, as needed.

During construction, piezometer data is collected and reviewed daily with respect to thresholds established during dam design. Other instrumentation near the construction is also monitored at an increased frequency. During non-construction periods, instrumentation is monitored weekly to quarterly, depending on the instrumentation type, location, and purpose.

A thorough review of instrumentation monitoring data is performed twice a year and is summarized in a memorandum to the facility. Additionally, an in-depth review of instrumentation monitoring data is completed as part of an annual dam safety inspection and report.

As shown in Table I, the number of instruments at the facility is significant, and the amount of monitoring data generated substantial. With such large datasets, there is the potential to become overwhelmed by the data, miss critical information, or foul the dataset through human error. These challenges have necessitated implementation of data management systems, as described later in this paper.

V. Site Surveillance at the Facility

A critical component of the Observational Method is site surveillance, which includes inspection and visual observation of the facility. Instrumentation provides valuable information that may not be visible to the human eye; however, there is no substitute for site surveillance. Surveillance at the facility is completed seven days a week by facility staff through visual inspection. The facility's tailings basin engineer and staff are equipped with Apple® iPad® tablet computers used to collect instrumentation measurements, take photographs, and record notes documenting site conditions.

Periodic site visits are also completed by the engineer of record to review instrumentation condition, collect measurements, document site conditions, and provide recommendations, particularly when unanticipated or noteworthy conditions develop.

A more thorough inspection of the facility is completed by the engineer of record and tailings basin engineer each fall as part of the dam safety program and consists of a walking inspection of the impoundment dams. Following completion of the inspection, an annual report is prepared documenting findings of the inspection, observations from monitoring data, and recommendations for subsequent action, if needed.

VI. Need for Integrated System

The preceding paragraphs have provided a brief overview of the types of data collected at the facility and their intended purposes. The paragraphs that follow describe the evolution of data management at the facility and the need for an integrated system.

A. Instrumentation Monitoring

Figure 1 illustrates the evolution of instrumentation monitoring at the facility. In the past, instrumentation monitoring data was recorded by facility staff using field notebooks and stored in Microsoft® Excel® spreadsheets. The data was then transferred to the engineer of record's Microsoft® Excel® spreadsheets.

As the amount of instrumentation monitoring data grew, the need for a data management system became apparent. In response, Microsoft® Excel® spreadsheets containing the instrumentation monitoring data were imported into a Microsoft® Access® database maintained by the engineer of record. This had the benefit of more securely storing data; however, the engineer of record quickly determined that Microsoft® Access® database plots were too rigid for the intended purpose. Therefore, data was exported daily from the Microsoft® Access® database and plotted in Microsoft® Excel® spreadsheets. This lacked efficiency but provided the required end product for data review and interpretation.

After several years of using the Microsoft® Access® database to store instrumentation monitoring data and Microsoft® Excel® spreadsheets to plot it, the engineer of record began using Tableau® plotting software. This allowed generation of customizable plots directly linked to the Microsoft® Access® database, significantly increasing efficiency. Data quality was also improved by reducing double handling. However, additional functionality was desired beyond what the Microsoft® Access® database and Tableau® plotting software were able to provide.

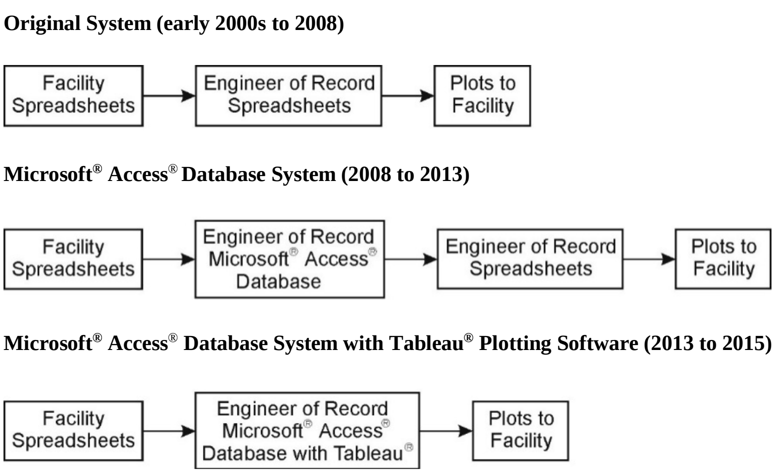

Figure 1. History of instrumentation data management systems at facility

B. Site Surveillance

Prior to implementation of the integrated data management system, instrumentation monitoring and site surveillance data were kept separate. Site surveillance data generally consisted of information collected by the engineer of record during periodic site visits and photographs from facility staff that were not regularly shared with the engineer of record.

More detailed information was collected during the annual dam safety inspection. Initially, notes were manually recorded using field notebooks and photographs taken with film cameras. Observations were later dictated into a voice recorder, although this procedure was short-lived due to the amount of time required for transcription. In the early 2000s, global positioning system

(GPS) cameras were used during inspections to geo-locate photographs, although the cameras' relatively short battery life was problematic in the field.

In 2012, data collection shifted to Apple® iPad® tablet computers that used a customized GIS application. The application allowed for collection of photographs and observation notes, each with GPS coordinates, which improved efficiency and accuracy. However, the application was used only for annual dam safety inspections and was not linked to instrumentation monitoring data.

Despite the improved efficiencies, it became apparent that a more integrated system was required. Recent improvements in tablet computer, database, and GIS technology presented the opportunity to create a new system integrating instrumentation monitoring and site surveillance data.

VII. Description of the Integrated System

After identifying the need for an integrated data management system, the following desired features were identified by facility staff and the engineer of record:

- Ability to store instrumentation monitoring and site surveillance data in a single or integrated system
- Ability to collect, store, and plot monitoring data for multiple instrumentation types
- Ease of access for engineer of record and facility staff using web-based interface
- Near real-time data availability for engineer of record and facility staff
- GIS-based interface to provide spatial visualization of data
- Secure data storage to maintain data stability and integrity

These desired features were used to evaluate a series of potential systems, as shown in Table II with the engineer of record's perceived facility benefits and limitations.

TABLE II
Data Management Systems Considered for Implementation at the Facility

System	Perceived Benefits [(1)]	Perceived Limitations [(1)]
US Army Corps of Engineers (USACE) Levee Inspection Tool	• Available to the public • Free	• Rigidity • Must be combined with other systems to handle instrumentation monitoring data • Reliance on third party
Vista Data Vision® (VDV)	• Commercially available • Designed for instrumentation monitoring data • Staff familiarity	• Would require substantial modification/configuration to achieve desired functionality
EQuIS Professional®	• Commercially available • Staff familiarity	• Would require substantial modification/configuration to achieve desired functionality
Esri® Collector for ArcGIS® with Microsoft® SQL Server® Database	• Commercially available • Customizable • Staff familiarity • Flexibility, particularly for future improvements	• Not turn-key • Development cost

(1) Perceived benefits and limitations are with respect to facility described in this paper at the time of evaluation and may not be true of all facilities

Based on the perceived benefits and limitations listed in Table II, the engineer of record identified the Esri® Collector for ArcGIS® application with Microsoft® SQL Server® database as the most appropriate systems for the facility. These systems were chosen based on their ability to provide the desired functionality and flexibility.

A schematic detailing the new integrated data management system is included as Figure 2. As shown in the figure, instrumentation monitoring and surveillance data is collected in the field using Apple® iPads® tablet computers with the Esri® Collector for ArcGIS® application. The field data is stored locally on the device until it is synchronized. The synchronizing process moves the data to an Esri® ArcSDE® (SQL) database, which functions as a transactional database. Each night the data from the transactional database is extracted, processed, and loaded into the Microsoft® SQL Server® database, where it is permanently stored. Data from the Microsoft® SQL Server® database is then made available on a website with a GIS-based interface for easy access, retrieval, and interpretation by the engineer of record and facility staff.

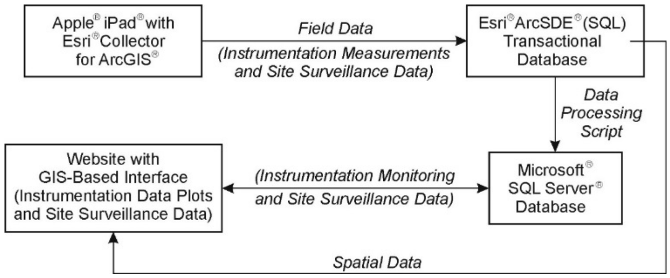

Figure 2. New integrated data management system

VIII. Advantages and Disadvantages of Integrated System

After nearly two years of heavy use, the advantages and disadvantages of the integrated system have become apparent and are shown in Table III. While these are specific to the facility, the information contained in Table III can be used by personnel at other facilities or engineers considering implementation of similar systems.

TABLE III
Advantages and Disadvantages of Integrated System at Facility

Advantages	Disadvantages
• Efficient data collection • Data centralization • Improved data quality through restricted user interface and elimination of double handling • Ease of access for facility staff and engineer of record • Ability to view data on mobile devices • Near real-time data availability • Easy collection and retrieval of geo-located photographs • Improved understanding of site conditions and changes for engineer of record	• Required implementation of multiple subsystems to achieve desired functionality • Risk of escalating costs due to customizability and ease of adding “just one more” feature • Reduced need for daily contact with data, making it easy to be too “hands-off” • Reliance on database programmers to resolve issues and implement changes • Challenges related to communicating engineering concepts to database programmers • Reduced flexibility compared to spreadsheets • Unanticipated impacts of third-party software updates (Apple®, Esri®, etc.) to integrated system

IX. Notable Successes

In the short time since implementation of the integrated data management system, there have been numerous successes with respect to monitoring dam safety and performance. The following paragraphs describe some of these successes.

A. Instrumentation monitoring thresholds

As part of the Observational Method used at the facility, it is imperative that instrumentation data be monitored and evaluated critically to identify unexpected behavior that may indicate the need for design modification. However, the automated nature of the integrated system can lead to limited daily contact with the data. Therefore, a threshold exceedance reporting tool was developed to notify the engineer of record when instrumentation measurements exceed limiting values defined during dam design. This has allowed the engineer of record to spend more time evaluating and interpreting data using the integrated system, as compared to previous systems in which significantly more time was dedicated simply to handling the data.

B. Monitoring and maintenance of relief well system

The threshold exceedance reporting tool has been particularly effective at identifying required maintenance cleaning of a relief well system at the facility. Due to the presence of the pressurized sand aquifer, relief wells have been installed along the perimeter dam toe in various areas to control pore-water pressures and maintain acceptable factors of safety against uplift. However, instrumentation monitoring data demonstrate that pore-water pressures gradually increase over time due to clogging of the relief well system between maintenance cleanings. With the integrated data management system, the increased pore-water pressures at piezometer locations can easily be compared to results from other relief well system monitoring devices and site surveillance photographs. Consequently, required maintenance cleaning of the relief well system is now identified by the threshold exceedance reporting tool, such that the cleaning is completed based on performance criteria as opposed to arbitrarily defined intervals that may not be appropriate.

C. Communication and documentation of site surveillance

As with most dams and related structures, facility staff provide valuable daily site surveillance, documenting normal operations as well as noteworthy changes or areas of concern. To be effective, this information must be promptly communicated to the engineer of record. This gives the engineer of record a better understanding of current conditions and the opportunity to assess developing situations that may require urgent attention. Based on this, several features have been included in the integrated system.

For example, site surveillance comments and photographs collected by facility staff using Apple® iPad® tablet computers are automatically distributed to other facility staff and the engineer of record each evening via email in a format that is accessible from any desktop or mobile device. The site surveillance data is also accompanied by inset maps showing the observation location and tagged with dam alignment station and offset information, which are automatically converted by the integrated system using coordinates from the Apple® iPad® tablet computer. The result has been a notable improvement in the engineer of record's awareness of site conditions in a manner that is convenient for facility staff. This promotes better discussion between facility staff and the engineer of record during weekly conference calls, thereby leading to more timely responses to changing conditions and greater understanding of site conditions that guide design and operation decisions related to dam safety.

Overall, the integrated data management system has established a central repository for all aspects of site surveillance: comments and photographs from the daily surveillance performed by facility staff, periodic site visits by the engineer of record, and the annual dam safety inspection by the engineer of record. Data was historically saved in various formats and in multiple locations across the computer networks of both the facility and engineer of record. However, with implementation of the integrated system, site surveillance data can be easily accessed and retrieved from a single website with GIS-based interface and interpreted by the engineer of record and facility staff.

D. Monitoring and evaluation of active seepage areas

The collection of site surveillance comments and photographs has been particularly effective for monitoring and evaluating active seepage areas across the facility. Within the dam safety community it is well understood that seepage is one of the leading causes of dam safety incidents and failures. However, many seepage issues that arise are unanticipated because, "the behavior of water depends, more than anything else, on minor geological details that are unknown" [2]. Given the length of dams at the facility, some degree of uncertainty exists regarding these minor geological details, and seepage has occurred at various times and locations.

In one case, active seepage over several hundred feet along the toe of an interior dam was observed during the annual dam safety inspection. The location of the seepage and associated observations were documented by the engineer of record using an Apple® iPad® tablet computer during the dam safety inspection. Over the following weeks and months, facility staff continued to collect photographs of the seepage conditions using an Apple® iPad® tablet computer. In addition to the site surveillance information being distributed daily via email for the engineer of record's review, data was also interfaced with GIS mapping available on the project website. This allowed changes in seepage conditions to be monitored over time by comparing previous photographs collected at the same location. As a result of the prompt and effective communication of the seepage conditions, alternative remedial actions could be evaluated by the engineer of record with the understanding that conditions were not worsening at the facility. Had this information not been available, other seepage control measures may have been prematurely implemented when more cost-effective and appropriate solutions were available.

In another instance, concentrated flow from the toe of a perimeter dam was observed during the annual dam safety inspection, concerning the engineer of record. After collecting photographs in the field using an Apple® iPad® tablet computer, the observations were automatically uploaded to the GIS mapping application for evaluation. Upon examination, it quickly became apparent that the location of the flow was associated with an underdrain documented in historical records, and that dense, grassy vegetation in the area had previously prevented the outlet from being observed. With the integrated system, an apparent concern was quickly determined to be a historical design feature that was functioning as intended. Facility staff continue regular site surveillance of the area and a weir box was installed and included in the integrated system for flow monitoring.

E. Integration of automated instrumentation monitoring data

Historically, instrumentation monitoring data has been manually collected by facility staff at routine intervals. However, due to the significant number of instruments at the facility, there was a desire to incorporate an automated monitoring system that would ease some of the demands on facility staff to collect readings manually.

To help evaluate the benefit of an automated monitoring system, a test section was implemented at a critical dam section. From this system, readings are automatically collected at regular intervals, stored within a permanent onsite datalogger, and transmitted via cellular modem to the integrated data management system in near real-time. The automated system has allowed for more frequent data collection than would typically be possible using manual measurements, and the connectivity with the integrated data management system provides the engineer of record near real time monitoring of one of the facility's critical dam sections.

X. Recommendations

Based on the authors' experience developing, implementing, and using the integrated data management system described in this paper, recommendations are made to those considering similar systems.

A. Involve the Engineer of Record

As instrumentation monitoring has become more sophisticated, there are a growing number of third-party vendors offering monitoring services. If a vendor is used to install instrumentation, set up monitoring systems, or store monitoring data, the facility should involve the engineer of record in the process. Instrumentation monitoring programs should be targeted and facility-specific. The engineer of record should be allowed to identify monitoring needs and have control of the data. Data means little if not combined with a thorough understanding of engineering principles and facility conditions.

B. Consider Network Requirements and Security Risks

We are in an age of easy data collection. Instrumentation monitoring systems, such as the one described in this paper, have the potential to generate large amounts of data that must be securely stored, particularly if the system is to be used for an extended period. Storage requirements should be considered before developing a system. Additionally, data security risks should be assessed. What are the consequences if the data falls into the wrong hands or if the data is corrupted or lost? How much data can be lost before it becomes an issue? These and similar questions should be carefully answered prior to developing a system.

C. Do Not Estimate Level of Effort from Experience using Microsoft® Excel®

While developing and improving the integrated data management system, the authors and their colleagues often used their experience with Microsoft® Excel® spreadsheets or similar software to judge the anticipated level of effort required to complete a task. Including a new data type in a spreadsheet may be as simple as pasting in the data, performing a few calculations, and creating a plot. However, with an integrated data management system, it is rarely that easy. Consideration must be given to the impact of the change on the various components of the integrated system and making sure the change is applied consistently across the system. For example, addition of a new instrument must be reflected in the Microsoft® SQL Server® database, the website with GIS-based interface, and Apple® iPad® tablet computer. While databases and integrated systems offer many advantages, it is often more labor intensive to implement changes than one may initially expect.

D. Clearly Define the Work Scope

Most engineers are not experienced software programmers. Therefore, there is a need to clearly define the work scope with the assistance of those who will be developing the system. It is also imperative to provide clear direction to programmers. Just as most engineers are not programmers, most programmers are not engineers. It is important to clearly communicate what is needed, provide a context for what is being done, and refrain from assuming that dam engineering concepts are immediately clear to those unfamiliar with the subject.

E. Avoid Scope Creep

The authors have found that it is often easy to fall into the trap of adding "one more feature" to a new system. If done right, stakeholders will be excited about the system, which is a good thing. However, this excitement often comes with a desire to add more. Those responsible for the system must be mindful of the agreed-upon scope and what can be done within the established budget.

F. Consider Staged Implementation

If possible, it may be best to implement a new system in stages. The authors have found that it is sometimes difficult to predict exactly how (and if) features will be used. Experience using some features can be used to more intelligently and strategically develop other features. While this extends the implementation schedule, it has the potential to result in cost savings and promotes development of a higher quality system.

G. Budget for Sufficient Review and Testing

The amount of review and testing is dependent on the size and complexity of the system, but should be considered an integral part of the development process. As with all software and database development, the first stage of review and testing should be completed by the programmers. Beta testing can be completed by engineers familiar with the facility and data prior to release of the system to the facility. It is recommended that the existing system be maintained during testing and the initial release of the new system for comparison and review purposes.

H. Stay Involved

With automation, there is a tendency to become too hands-off. It is important that those responsible for the system continue the vetting process after initial rollout to ensure it is functioning properly. It is also important that the user continue to scrutinize the data and system using engineering judgement to ensure that the data is reasonable.

I. Responsible Staff Must Serve Two Roles

The authors have found that those responsible for the system must perform key functions as both the system administrator and engineer. The system administrator should be responsible for keeping the system running properly and acting as a liaison between programmers and the system users. The engineer should be responsible for monitoring, evaluating, and using the data. While both roles can be filled by a single person, it is often beneficial to have separate individuals; it is sometimes difficult to view the system and data from both perspectives.

J. Remember Long-Term Costs

Rarely does a database remain static. More often than not, improvements will be desired, and maintenance is a certainty. Additionally, software licensing and data storage costs will continue through the life of the system. It is important for developers of these systems to communicate long-term costs to the client at the front end of system development. It is also important for developers to commit to the system long term and to have redundancy in staff to allow seamless transitions and timely response to improvement and maintenance needs.

XI. Summary

Due to the complex nature of geotechnical challenges presented by the construction and operation of tailings impoundment dams, a large investment in instrumentation monitoring and site surveillance is required and has the potential to generate large quantities of data. This data is only valuable if it can be stored, retrieved, and interpreted efficiently. With recent developments in tablet computer, GIS, and database technology, there is an opportunity to leverage these technologies to better handle large datasets.

The preceding paragraphs have described the development and use of an integrated data management system to handle large quantities of diverse data. After two years of use, the system has proved to be valuable to both the engineer of record and the facility. Several lessons were learned from the process, which can be used by others considering implementation of similar systems.

XII. Acknowledgments

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