TVA'S INSTRUMENTATION AND MONITORING PROGRAM — HELPING MANAGE RISKS ASSOCIATED WITH WASTE IMPOUNDMENTS

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ABSTRACT

TVA is responsible for the operation and safety of 22 waste stacks associated with its 11 coal-fired power plants located in 3 states. These stacks store various combinations of fly ash, bottom ash, and gypsum with a combined surface area of approximately 1680 acres. Fly ash comes from the removal of particulate matter from the exhaust stacks. Bottom ash is the residuals left from burning coal. Gypsum is a byproduct of the removal of particulate matter from the exhaust stacks. Historically these materials were transported to the disposal areas by pipeline and sluiced into position behind dikes. The dikes are raised by constructing perimeter embankments of local materials and in some cases using the waste materials. Most raises occurred using the upstream method in which each new dike is placed on top of the older dike but shifted inward. The dikes have typically impounded standing water for their operational life which has resulted in them being managed as dams.

In 2008, after the catastrophic failure of one of these stacks at Kingston, Tennessee, TVA undertook a major program to upgrade its performance monitoring program to a real-time monitoring system that gives advanced warning of unexpected performance. Primary potential failure modes were identified for each active waste stack and a monitoring program was developed to indicate early stage development of each significant failure mode. Instrumentation was installed and a real-time data collection and management system put into place. Currently this system monitors more than 5,400 sensors logging more than 17,000 readings per hour.

This paper describes the factors used to design the monitoring system, the key components of the system, and examples of how it is used to help manage TVA's risk for these facilities. The benefits of the instrumentation and monitoring approach as a risk management tool are discussed. Lessons learned from the implementation and operation of the system are described so that other owners of similar facilities might benefit.

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INTRODUCTION

TVA currently has 11 coal-fired power plants with 46 active generating units located in Tennessee, Alabama, and Kentucky. These plants can produce up to 81.4 billion kilowatt-hours of electricity in one year which accounts for about 57 percent of TVA's power generating capability. Since the large failure at its Kingston facility in 2008, TVA has begun closing all wet ash systems. The closure of wet ash storage systems consists of building ash and gypsum dewatering facilities, constructing new dry storage landfills, and closing existing ash and gypsum ponds. This plan is expected to cost 1.5 to 2 billion dollars over an 8 to 10 year period.

On December 22, 2008, the north and central portions of the cell 2 ash disposal area dike failed, releasing an estimated 5.4 million cubic yards of fly ash slurry at the Kingston Fossil Plant in Roane County, Tennessee. The fly ash slurry flowed across the Emory River Channel and over the Swan Pond Creek flood plain, approximately 3200 feet beyond the limits of the original ash pond. It was estimated that 42 residential properties were affected by the failure and 22 properties were evacuated. No injuries were reported as a result of the failure. Cleanup has cost TVA more than $1.2 billon to date.

TVA contracted AECOM to perform a root cause analysis and find the cause of the ash spill at the Kingston Fossil Plant. They determined there were four key factors that lead to the failure (Walton, June 25, 2009). First, the dikes of the dredge cell were built using the "upstream method", by which each new dike added to a facility is built on loose sluiced ash. The most recently constructed dikes were built on loose, sluiced fly ash 200 feet inward from the original dike, which itself was built on more stable foundation conditions. Second, the dredge cell footprint decreased in size as ash was added and more cell height was required to accommodate the same ash volume. Consequently, the elevation of the ash was increasing faster and faster with each passing year. Third, creep deformations had developed over time due to loose slimes which were deposited early in the ash pond's history. These slimes had high water contents, high liquidity indices, and low undrained shear strengths upon which 40 to 85 feet of loose wet ash was placed. The final cause of the failure presented in AECOM's analysis was the loose wet ash itself. The initial sluiced ash had a high void ratio as a result of being deposited under water and didn't benefit from consolidation under the surcharge weight placed above these deposits. This resulted in the sluiced ash remaining very loose with a low undrained shear strength. The combination of these factors resulted in a global stability failure and the release of a large volume of fly ash. TVA then undertook a massive evaluation of the stability and safety of all of its active ash storage facilities.

One of the outcomes of this evaluation was the development of an instrumentation and monitoring program to monitor the stability of the Coal Combustion Products (CCP) disposal area structures. Specifically, the pore water pressures within the containments would be monitored by reading the depth of water in standpipe piezometers (PZ) and subsurface slope movement would be monitored by reading deflections of slope inclinometer casings at planned intervals. The CCP Instrumentation and Monitoring Program became integral to TVA's risk management program by:

- Helping demonstrate that each facility is meeting TVA's performance objectives.
- Indicating unacceptable or questionable performance to draw attention for further examination.
- Indicating unacceptable performance in sufficient time to allow remedial measures to be implemented.
- Collecting associated data and information to help interpret data from the instrumentation.
- Presenting all relevant information in an organized, expeditious manner to allow timely evaluation of the safety of a facility for any particular condition.
- Indicating where modifications to the monitoring program and operating practices are required.

DEVELOPMENT OF INSTRUMENTATION PROGRAM

Safety assessments in 2009/2010

In 2009 and 2010, TVA performed a series of geotechnical explorations and slope stability evaluations at the 11 active coal-fired power plants. The assessments were made in order to determine whether present conditions indicated an unstable condition that could cause a release of waste materials into the surrounding environments. The study of each site began with a review of historical information and site inspections, after which a geotechnical exploration plan was developed and implemented within each site's disposal areas.

Representative cross sections were developed to reflect typical conditions for each facility and a series of explorations were made that consisted of drilling borings, taking samples and installing piezometers. Subsurface investigations included Standard Penetration Testing (SPT), Cone Penetration Tests (CPT), and undisturbed soil sampling. Borings were generally positioned at the dike crest, mid-slope and toe areas of the representative cross sections. Most borings were advanced to apparent bedrock or into firm natural material.

Subsequent laboratory testing consisted of classification, moisture content, permeability, and shear strength testing. Data from the drilling and laboratory testing program were used to perform slope stability and seepage analyses in order to quantify factors of safety for current conditions. The seepage analyses helped estimate seepage gradients for the evaluation of piping potential, and pore water pressures within dikes and foundation soils for use in the slope stability analyses.

Dikes and ash stacks were assessed under static, long-term, steady state, and rapid-drawdown conditions. Factors of safety were developed using Spencer's method of analysis, circular slip surfaces, and search routines that helped identify the critical failure surface. Slope stability models were then evaluated using both pore pressures predicted with the seepage models and data from piezometer readings. The new information and analyses showed multiple cross sections with factors of safety for global stability less than 1.5, the minimum factor of safety required by TVA for long-term, static loading conditions. Evaluations also identified areas of inadequately controlled seepage. TVA undertook work to improve these locations including re-grading of perimeter ditches, slope flattening and the installation of riprap, and the installation of toe buttresses and toe drains to improve surface drainage and reduce the ponding of water. Operations and Maintenance Manuals were developed. An instrumentation and monitoring program was formulated and implemented for each facility to provide indications of developing potential failure modes so risk mitigation measures could be deployed when required.

INSTRUMENTATION PROGRAM

The purpose of the instrumentation was and is to monitor the stability of the CCP disposal area structures. It focuses on providing indications and warnings of the following potential failure mechanisms:

- Slope instability due to high pore water pressures in the interior of the slope.
- Slope instability due to lateral movement within the slope from whatever cause.
- Overtopping of the retention dikes by stored water.
- Unexpected loss of containment as indicated by an unexpected decrease in pond water level.
- Occurrence of significant precipitation.
- Occurrence of a significant earthquake.

The CCP Instrumentation and Monitoring Program is integral to TVA's risk management program by:

- Providing actionable up-to-date information on the performance of the impoundment structures.
- Indicating unacceptable performance in sufficient time to allow remedial measures to be implemented.
- Indicating unacceptable or questionable performance to draw attention for further examination.
- Providing other information, including historical records, relevant to the interpretation and understanding of performance monitoring data.
- Organizing data and information in a format that facilitates rapid and efficient interpretation.
- Helping demonstrate that the facility is meeting TVA's performance objectives.

Types of instruments chosen and why

The following describes the different types of instruments installed and the purpose of each.

Piezometers – Slope stability of these stacks depends directly on the nature of flow and pore water pressures within the stacks. Piezometers were installed at representative locations to define phreatic conditions and indicate pore water pressures. Standpipe-type piezometers were installed in borings advanced using 3 ¼ inch internal diameter (ID) hollow stem augers or 4¼-inch (ID) hollow stem augers. Either 5-foot or 10-foot long slotted screen piezometers were used with the boring fully grouted above the top of the screen to create a seal. The piezometers were typically installed in upper and lower dikes as part of the overall stability evaluation to provide data within the existing dikes and native foundation soils.

Inclinometers - Slope movements serve as early warning signs of impending instability. Horizontal inclinometers provide very good measurements of horizontal movement within a slope. Inclinometer borings were outfitted with 2.75-inch (ID) slope inclinometer casings which were grouted in place with bentonite-cement grout. These were generally placed at the outer edge of the top of the waste stack at representative locations.

Survey Benchmarks and Settlement Monuments – Due to construction techniques and materials used in many of the fossil impoundment structures there was concern about continued long term deformations from consolidation of the waste materials. Survey benchmarks and settlement monuments were installed as part of the monitoring program for embankment stability monitoring. These instruments are read manually by TVA's surveyors on an annual basis.

Water Level Sensors – Pore pressures and seepage conditions within the slopes depend on the pond levels and river levels. Pond and river level gauges were installed throughout the active fossil plants to measure surface water levels in each impoundment.

Typical instrumented section

A typical instrumented cross section is shown in plan in Figure 1 and in section in Figure 2. Figure 1 shows the containment berm built of natural soils with two benches. The grey-white material on the right side of the photo is stored ash.

Note: Figure is a screen capture from the iSiteCentral monitoring system. Aerial photo is scaled to project coordinates. Section and instruments are geo-located in a layer overlying the aerial photo. Circles indicate locations of instruments. Number in circle indicates number of sensors at each location. Green color indicates all sensor readings are within their normal range. Light colored material in the photo is rock material added to fortify the slope.

Figure 1. Plan for Section of Cumberland

The cross section in Figure 2 has a red dashed line showing the critical failure surface for global stability. The upper orange dashed line shows the phreatic surface used by the geotechnical engineers to assess global stability in 2010-2011. The analyses calculated the pore pressures for the entire cross section using this piezometric surface. Vertical blue lines indicate pore pressure measurements made in 2012 using grouted in place piezometers. The bottom of the line indicates the elevation of the sensor. The top of the line indicates the piezometric head measured by the sensor. All piezometers in the lower part of the cross section indicate pore pressures much less than one would obtain using the shown phreatic surface. Using the measured pore pressures rather than the assumed single phreatic surface resulted in a significant increase in the calculated factor of safety for global stability for both static and earthquake loading. The data from these piezometers helped TVA avoid significant remedial work and save millions of dollars.

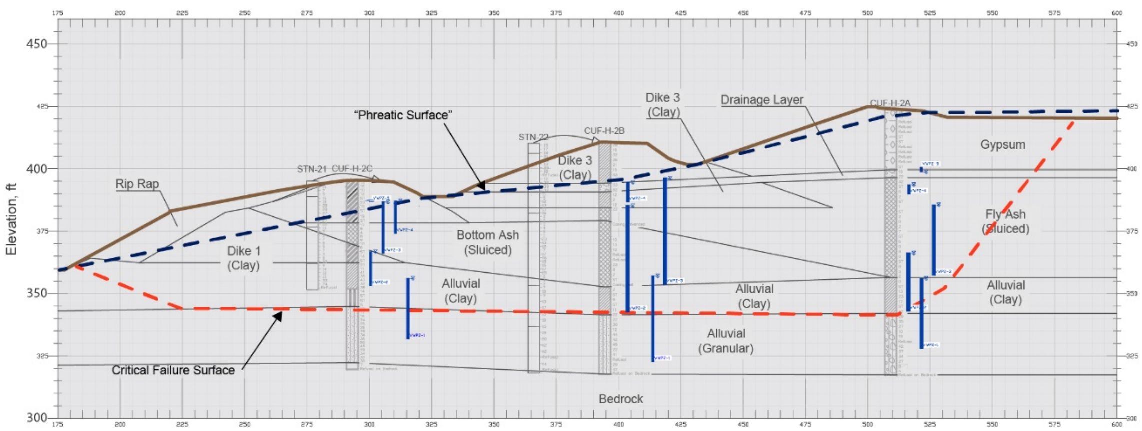

Figure 2. Cumberland Cross Section

Automation

After the Phase I instrumentation program was complete, it became apparent that conditions could change quickly within a stack and that manual readings could not be obtained quickly enough to derive maximum value from the instrumentation and monitoring program. TVA decided to implement an automated instrumentation program that would provide data every five minutes on key metrics of stack stability. Most of the standpipe piezometers were retro-fitted with Geokon 4500S Vibrating Wire Piezometer Sensors connected to data loggers. The inclinometer casings were retrofitted with Geokon In-Place Inclinometers Model 6150 connected to data loggers. The Pond and River Level sensors were likewise automated. Weather stations to measure rain, wind, temperature and barometric pressure were also installed at each site to provide supporting data.

Data Acquisition and Communication

Campbell Scientific CR1000 data loggers with AVW200 vibrating wire interface modules are used to power the sensors and convert sensor outputs to digital readings. These data are transferred to a base station at each site using spread spectrum radios. An

IP or Internet modem at each site receives the radio signals and forwards them to the central data servers at TVA's headquarters in Chattanooga, Tennessee. Figure 3 shows a typical installation of data logger, solar power supply and radio at an instrument location.

Figure 3. Typical TVA instrument station

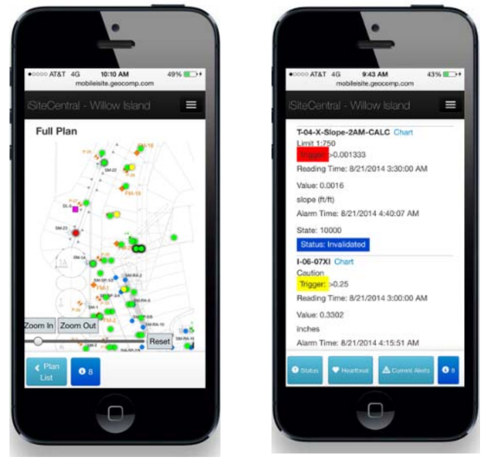

Figure 4. Software app showing sensor status

Experience at TVA has shown that conditions can change over a few minutes so electronic instruments are read every five minutes and the readings are compared to previous readings and preset limit values. Manual readings of non-electronic instruments are taken by TVA personnel and then input into TVA's data management system while the person is still at the instrument location. This is done using a software app on a phone or tablet. Figure 4 shows one app that gives a map showing instrument locations and sensor status as well as a screen that displays the current reading of any sensor.

DATA AND INFORMATION MANAGEMENT SYSTEM

With the need and ability to collect data from more than 5,400 sensors every five minutes, TVA realized the need for a comprehensive real-time data management system to store, maintain and report these data as needed. TVA contracted with Geocomp to provide a secure and robust data management system that enables TVA users to access all data at any time to help them evaluate performance and risk of their ash storage facilities. Geocomp provided TVA with a server-based system that receives data from the field data loggers via IP connections, converts the raw data to engineering units, stores the information and reports the data in a variety of formats to TVA personnel as needed. The system uses a web browser- and GIS-based graphical user interface which allows users to navigate and access the system quickly and intuitively. Data are stored in a Microsoft SQL database. The system provides a number of useful features:

- All raw instrumentation monitoring data, both for manually and automatically read instruments are stored in the system for the complete record of data collection. This permits adjustments to calculated values if calibration settings need to be changed.

- Raw data are converted to engineering units using the associated calibration factors and/or other sensor data for correction (for example, barometric pressure corrections for piezometers). These calculated values are stored to facilitate rapid data portrayal. They are recomputed if calibration settings change.
- Customizable tables and charts can be created that present either raw or calculated data with their respective threshold and limiting value performance limits if these have been defined.
- Charts and tables are presented in customized reports which are also accessible on demand through the web interface providing TVA with an efficient and reliable reporting system. Each user can create and save his/her private charts and tables and share any of these globally.
- TVA's iSiteCentral GIS system has the functionality to send alert notifications whenever performance limits (threshold values and limit values), defined by TVA or their Engineering Design contractors, are exceeded.
- A chronological performance history is included for each site with each performance incident, such as a crack, a slip, or a pipe washout, defined in space and time with the locations of these incidents shown on a topographic plan or aerial photo.
- A collection of documents, photographs, plans, maps and aerial photographs over the life of the facility that catalogue information relevant to the evaluation of the performance of the facility and make this information readily available from within the TVA iSiteCentral platform. Historical topo maps and aerial photos can be viewed as GIS layers to show changes over time.

Description of the TVA iSiteCentral GIS system

A TVA engineer's ability to assess and manage the risks associated with their areas of responsibility is directly affected by the quality of data and observations available, the timeliness of the data being delivered, analysis of the data in context with other information, and the actions that are required as a result. As noted before, there is a significant amount of data (13,000 readings per hour every hour of each day) coming into the TVA iSiteCentral GIS system, so much that it would be overwhelming for a person or group of persons to evaluate without using an automated system.

To aid in this process, TVA's iSiteCentral GIS system provides a map-based portal to access performance data, documentation, and historic information relevant to the CCP disposal areas. It also proactively provides automated data collection, processing, and alarming services to identify field performance issues for TVA engineers so that they can focus their efforts and act as appropriate.

A schematic diagram showing the data flow and services being performed automatically by TVA's iSiteCentral GIS is shown in Figure 5. The automated instrumentation data are collected on field data loggers on pre-programmed intervals. The typical configuration on most sites is one reading every five minutes for the weather station, piezometers, pond level indicators and river level indicators; and one reading every hour for the in-place inclinometers. The data collected are uploaded into the TVA iSiteCentral system.

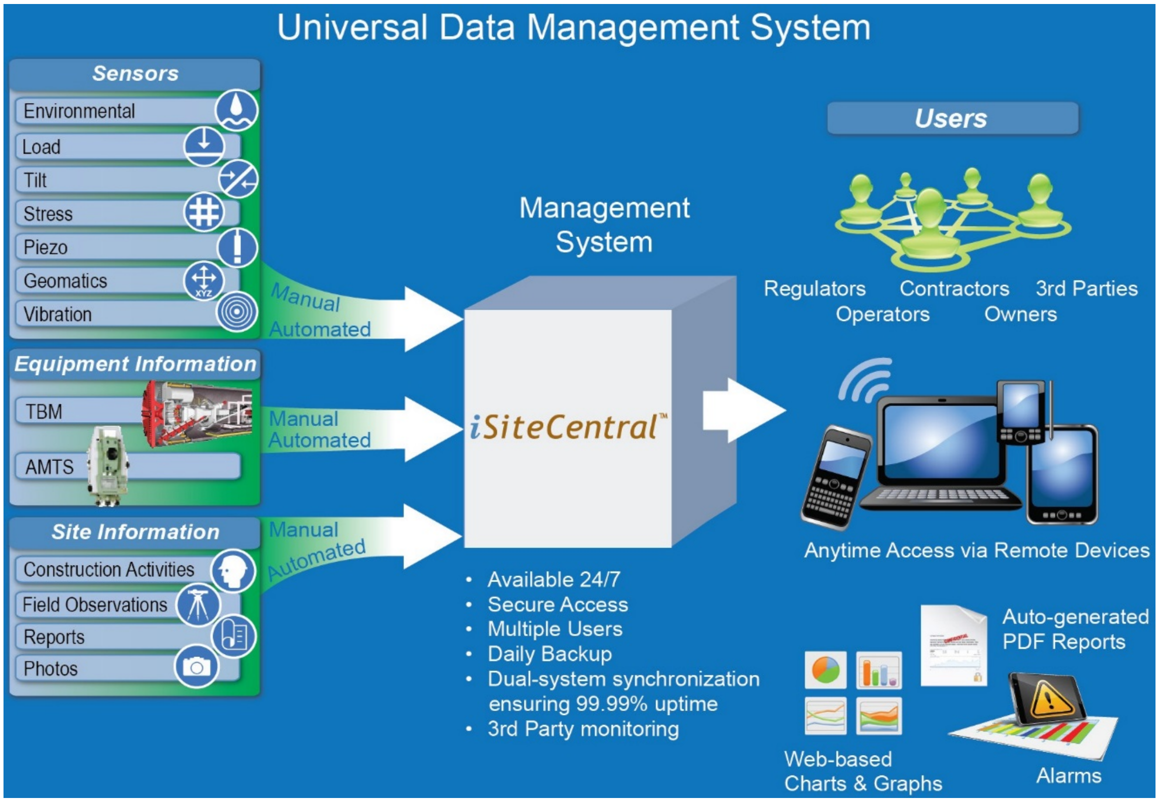

Figure 5. Information Flow in TVA's iSiteCentral GIS System

Several services are running on TVA’s iSiteCentral system to identify actionable issues in the data stream. These include:

Heartbeats – the system has a user-defined threshold called the *Heartbeat Span*. When the time between the current time and the last posted reading exceeds the Heartbeat Span, an alert like that shown in Figure 6 is issued to indicate that something is not working to deliver data when expected. The Heartbeat Span is configurable for each individual sensor or as groups of sensors. Heartbeat Jobs are created and scheduled for any list of sensors and any user or user group.

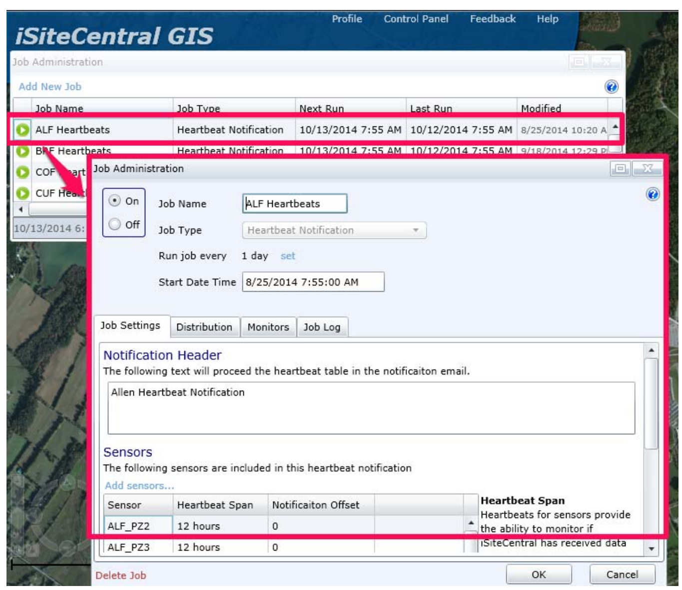

Figure 6. Heartbeat job detail

System Health alerts provide an early warning of potential data processing issues, malfunctioning equipment, or communication failures.

Invalid/Erroneous data are flagged and removed from charts, tables and reports but remain in the database for troubleshooting.

Rainfall Alerts – One driving force behind some potential failure modes at the CCP disposal facilities is heavy rainfall. TVA's iSiteCentral has two focused services to identify and track rainfall events. The first is an integrated reporting of NOAA's weather station alerts and access to NOAA's weather data. Heavy rainfall warning notices like that shown in Figure 7 are delivered to users to focus additional attention to the monitoring where and when appropriate. The second is a rainfall event tracking algorithm developed to provide information on storm severity (i.e. a 50 year storm) based on NOAA's published analyses. TVA uses this information to mobilize field staff to perform visual monitoring and inspection procedures so consequences of heavy rainfall can be identified early and managed.

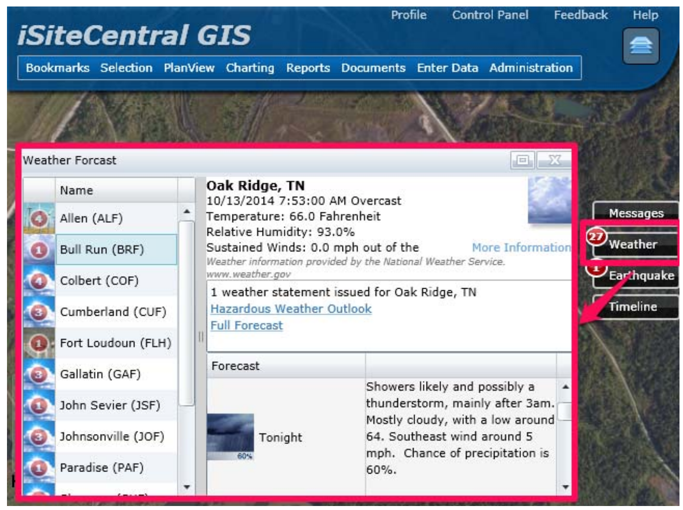

Figure 7. Rainfall Alert

Earthquake Alerts – The TVA has regulatory requirements to assess and report on any significant earthquake events that occur at their CCP Disposal facilities. These facilities are exposed to shaking primarily from the New Madrid fault system. TVA's iSiteCentral monitors the USGS earthquake's real-time reporting feeds, and issues alerts based on the specific criteria associated with TVA's regulatory obligations.

Sensor Alerts – A Limit Level reading and Alert Level reading is established for each sensor. Email messages are sent whenever these levels are exceeded and TVA initiates a pre-planned action plan. The Alert status of all sensors at a site are shown in color code on a plan of the site to provide an overall quick visual impression of the status of a site.

Each user in the system has a managed view into the system (i.e. the project administrator determines what sensors, information, and features a user can access). For TVA's iSiteCentral services listed above, a user's managed view is always enforced. This means that if a user is an active participant in a heartbeat job, but does not have permission to view the data for all sensors configured in the job, then that user will only see an alert message for the sensors it is permitted to see/view. This allows flexibility to deploy alerting services without confusing users with alerts on sensors/data for which they are not responsible. One useful application of this feature is to direct alerting messages on system performance to operations and maintenance (O&M) staff and messages on performance alerts to the Engineering staff. For example, Engineering staff don't need to be bothered by messages about a failing power supply that needs attention by O&M staff.

Typical use cases

Rain Data - Rainfall notifications are programed to alert engineers, field staff and management when threshold events are exceed. At least three events in 2013 and 2014 triggered field staff and operational staff to mobilize to several CCP impoundments and visually monitor saturated slopes and swollen ponds. These notifications helped TVA to successfully reduce risks from overtopping of dikes and slope instability.

Unusual Performance - On August 1, 2014, TVA field staff reported to TVA's engineering group a perceived potential problem in an ash pond at the Shawnee facility. At the time, unexpected bubbles were reported in the pond which could indicate water flowing out of the pond through an abandoned pipe or sinkhole. This observation concerned field staff as prior failures of this type have occurred. TVA used the iSiteCentral GIS system to evaluate the problem. The pond had been outfitted with an automated pond water level sensor. TVA accessed the data from the pond sensor (including historical information) to determine that there had been an unexpected decrease in the pond level elevation. The data were confirmed to be accurate. The change in pond level was determined to be directly related to dredging activities occurring at the site. TVA stopped the dredging activities and the pond level returned to normal.

Exceeding Threshold and Action Levels - During the last year, TVA has experienced multiple rainfall events that have produced saturated soil conditions and as a result increased pore pressures in the CCP impoundments. These increased pore pressures have caused multiple threshold levels to be exceeded which resulted in the following activities:

- Field personnel called to each area and visual inspection performed.
- Manual verification of automated readings.
- Slope stability analysis performed modeling existing conditions.
- Modification of slopes and operating procedures to increase factor of safety where warranted.
- Adjustment of threshold levels if factors of safety remained above acceptable criteria for steady state conditions.

PROJECTED BENEFITS OF THE TVA INSTRUMENTATION AND MONITORING PROGRAM

There are many projected benefits to the TVA instrumentation and monitoring program by using iSiteCentral GIS. Many of these benefits have been achieved already and are discussed below. These benefits will continue through and beyond final closure of these waste storage facilities.

Both the operations/maintenance group and the engineering group at TVA currently benefit from the early warning system that is part of TVA's iSiteCentral GIS system. Messages in the form of emails are sent to select members of TVA operations/maintenance group to notify them when a sensor needs maintenance and/or additional attention. With approximately 5400 sensors at TVA facilities, this is extremely helpful in tracking and scheduling maintenance needs. The engineering group staff also receive notifications for instrumentation readings that exceed specific threshold and action limits. This brings immediate attention to evaluate the readings and determine what action is required. Alerts also in the form of an email are sent to TVA staff including members of the engineering group and representatives at the individual facilities for a rain event that exceeds a specified amount. This information allows TVA to be alert to possible changing site conditions related to weather events. All notifications from the iSiteCentral GIS system allow for early identification and detection of unexpected or undesirable performance by TVA.

TVA's engineering group has access to vast amounts of current and historical data and documentation which is stored in one central location – TVA's iSiteCentral GIS System. The data and information management system includes material in relation to instrumentation such as boring logs, installation logs, both manual and automated data, photos, cross sections, reports, historical timelines, and site development plans. TVA staff can create charts, tables and reports directly from iSiteCentral GIS. The categorized data allows for easy access to information TVA staff need to evaluate real time issues and make informed decisions about site conditions and the possible need for additional action. If no action is necessary, TVA staff can continue to follow trends over time and look for cause and effect relationships.

LESSONS LEARNED

Advancements in logger technology and planned changes in field system configuration and data migration are being integrated to improve the overall system:

1) The field data loggers will be equipped/updated with new capability to serve data over a TCP/IP connection, and published to authorized users in XML format via a password-protected HTTP connection, and
2) The remote connections, which are currently IP modems on the local cellular networks, will be modified to transmit data via the TVA's LAN network at each site.

These changes will: reduce the lag-time between data collection and data posting/alerting in TVA's iSiteCentral GIS; make the data transmission more secure and less costly; provide a redundant means of data collection (i.e. XML data feed and conventional data files); and provide easy review of current readings by field staff without using data logger-specific software. Ultimately the monitoring systems will be more interactive and event-driven. For example, a heavy rainfall warning from NOAA, an Earthquake event alert from USGS, or an Engineer observing some event/activity in the field can automatically trigger more frequent data collection and reporting.

During the initial system development, the focus was on collecting and reporting data from the instruments as quickly as possible to support TVA's engineering assessments. It soon became clear that rapid assessment of the data required rapid access to historical information, current geometry, subsurface information and other documents to provide context to the instrumentation data. An extensive document management system was added that provides these materials using the same GIS platform. Documents in electronic form are tagged with time and location data so they can be correlated with the instrument locations. This feature allows an engineer making an assessment of the instrumentation data to readily obtain information about the subsurface conditions, sequence of development of the slope, history of performance, installation details for the instrument and other information to help determine what the measured data mean.

During deployment it became attractive to consider making it possible for on-site people to add information and data to the database and to see results from the system using mobile devices (cell phones and tablets). Specific software apps have been developed to enter manual readings, add field observations, provide inspection reports, view measurements for a specific instrument and add annotated, geo-referenced digital photos. These capabilities are greatly enhancing the effectiveness of the field activities.

CONCLUSIONS

TVA uses a proactive, near-real-time performance monitoring program to identify undesirable performance and potentially harmful events at the earliest possible time so proactive, mitigation activities can be performed. This approach is an integral part of TVA's risk management program to reduce the probability and consequences of a failure of any of its waste impoundments. This program provides several significant services to TVA personal including:

1. Providing important data and related information on facility performance in near-real-time in a presentation platform that enables efficient and accurate evaluation and interpretation.
2. Providing information on the historical development and performance of each facility, subsurface information and other useful documents to provide context to the measured performance data and aid in its interpretation.
3. Providing component status information so that the monitoring system can be kept fully operational, reliable and believable.
4. Providing alert messages on significant events that require TVA attention and action.
5. Enabling TVA to do a more comprehensive performance monitoring program with less operational resources and enabling its staff to focus on data interpretation and action rather than data gathering.

This work to obtain a central platform to store, manage and review instrumentation data and related information has been very successful in helping TVA to streamline its processes and work flow related to field monitoring of the performance of its waste impoundments. TVA is planning to expand this approach to other data intensive operations, such as groundwater and water quality monitoring.

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