INSTRUMENTATION DATA ACQUISITION AND MANAGEMENT AT SALUDA DAM

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ABSTRACT

Saluda Dam Project is the largest ongoing seismic dam remediation project in the United States. Remediation includes construction of a new Dam directly at the toe of the existing earthen embankment built in the early 1930s. The Saluda Dam is classified as high-hazard. The city of Columbia (population 400,000) is 10 miles downstream. In the event of a breach, the city would be a subject to flooding, almost certainly involving loss of life. Construction at the toe of a 200-ft tall dam, impounding a 2,100,000 ac-ft reservoir is a dangerous task. The concept demands a detailed, effective Instrumentation and Monitoring Program to ensure safety and stability of the existing Dam, while a new Dam is being built.

The Monitoring Program, developed by RIZZO, consists of two equally important parts: Instrumentation and Visual Observations. Instruments include more than 130 piezometers, 100 inclinometers, 8 tiltmeters and numerous shear strips and laser lines. This paper addresses topics such as choice of instrumentation and installation techniques, and discusses what worked and what did not. With hundreds of instruments to install, choice of an inexpensive and fast installation technique was an important task.

Developing an efficient data acquisition and management system was important to the success of the Program. RIZZO utilized multi-channel data loggers, radio links and a wireless network to deliver real time data directly to the main computer for interpretation. The paper presents an overview of the automation system setup, discusses data quality control methods and addresses encountered problems.

Obtaining real time data from hundreds of instruments, although a very difficult task on its own, is not nearly enough for a successful Monitoring Program. The key is listening to the Dam, reading the signs, interpreting them and making recommendations based on the collected information. How much information is too much, relative to the risk of unknowns and potential cost of construction delays? Did we install enough instruments and in the right places? Do they correlate with construction activities and visual observations? These are just a few puzzles RIZZO had to solve.

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INTRODUCTION

This is the last in a series of papers written by the authors on the Instrumentation and Monitoring Program implemented at Saluda Dam. Saluda Dam is a 75-year-old 200-ft-tall and 1.5-mile-long earth embankment located near Columbia, South Carolina. The Dam is currently being remediated to prevent catastrophic failure due to liquefaction during a seismic event. The remediation involves building a dry dam at the toe of the existing one that would serve as a water retaining structure if the existing dam fails. The first paper, “Dangerous Place to Dig” (Ref.5), addressed the analyses and design. One of the biggest challenges engineers faced was designing an open cut excavation at the toe of such a large dam. Draining the lake was not an option, so excavation had to be performed with essentially full pool, making conditions even more dangerous. To minimize the risk, it was decided to excavate and backfill in small portions, or cells, use extensive dewatering of the Dam and foundation, and work around the clock to limit the time excavations stayed open. Even with these precautions, excavation is the time when the Dam is the most vulnerable and when careful monitoring of conditions is a must.

Engineers developed and implemented a comprehensive Instrumentation and Monitoring Program. The program uses the observational approach advocated by Dr. Ralph Peck (Ref. 4). It emphasizes a “listening to the Dam” concept by interpreting the data, correlating it with construction activities and staying a step ahead. The second paper in the series, “Listening to the Dam” (Ref. 6), described the overall philosophy and gave examples of this approach at work. For this paper, we selected steps dealing with technical aspects of the instrumentation and illustrated the thought process for each of them. The paper provides rationale for how and why certain instruments were chosen, the locations they were placed, discusses automation options and describes the “nuts and bolts” of the data acquisition system.

SELECTION OF INSTRUMENTS

To select the instruments engineers first had to identify potential problems and their trigger mechanisms, define the geotechnical questions that need to be answered and select parameters to be monitored. In this case, the main concerns were global stability of the dam and local stability of the excavation. Several construction activities were identified as having a potential impact on Dam stability:

- Dewatering of the embankment fill and its foundation;
- Excavation at the toe;
- Construction of a haul road for heavy CAT 777 trucks above excavation; and
- Partial pool drawdown.

The primary instruments to detect and predict slope failure or bottom heave are piezometers and inclinometers. Inclinometers measure subsurface deformation caused by slope movement. Piezometers measure pore pressure within the embankment and foundation soils. Inclinometers were supplemented by surface monuments/surveying and laser lines. Data from these instruments was used to identify the extent of any movement
and to guide subsequent remedial actions. The driving factors in selection of instruments were ease and speed of installation, minimum interference with construction, automation capability, durability, and reliability.

For inclinometers, engineers decided to go with standard Slope Indicator products (Ref. 8) because of previous experience with the field equipment and data interpretation software.

Deciding on the type of piezometer was more difficult. Prior to construction, the Dam was equipped with open standpipe (Casagrande) piezometers. These instruments proved to be reliable and easy to use, however, they did not fit requirements for the new installation (fast installation, quick response time, ability to measure negative pore water pressure, automating capability, and minimal interference with construction). Engineers considered pneumatic and vibrating wire (vw) piezometers, but decided on vibrating wire mostly because of previous experience and familiarity with the product. Vibrating wire piezometers “pluck” a wire attached to a diaphragm. As the tension in the wire and thus its vibrating frequency vary in proportion to the pore pressure against the diaphragm, the pore pressure can be determined. Two of the typical concerns with vw piezometers are lightning protection and long-term reliability. In our case, the model that was chosen has lightning protection built in, a plasma surge arrestor. Long-term reliability was not a concern either because the construction monitoring program was only scheduled to last less than two years.

The next step was choosing a model and finalizing the details. To help with the decision, a field test program was designed. Research suggests that a sand pack is unnecessary with vibrating wire piezometers, that is piezometers can be simply grouted in a borehole (Ref. 3). Elimination of the sand pack reduces installation time and simplifies the process. Despite the promising research, concerns about site-specific performance of a fully grouted piezometer remained. The field test was performed to compare measurement of pore pressure with 1) standard vw piezometers (Geokon 4500S) in sand pack, 2) spring-activated vw piezometers (Geokon 4500MLP) fully grouted in borehole, and 3) Casagrande-type piezometers. First, two boreholes were drilled next to an existing multi-level Casagrande-type piezometer. Two standard vw piezometers, one in foundation soil and one in the embankment, were installed in one of the new boreholes. Transducers were in a 1-ft-thick sand pack and located at the same depths as the screen intervals of the Casagrande-type piezometer. Bentonite pellets were poured on top of the sand packs to create a 0.5 ft-thick plug. The remaining borehole was then grouted with a Portland cement and high yield bentonite mix grout, consisting of two 94 lb. bags of Portland Type I cement and two 50 lb bags of high yield bentonite mixed in 150 gallons of water. In the other borehole, spring-activated vw piezometers were placed at the same elevations. Once the springs on the piezometers were activated to hold the transducers against the borehole walls, the entire borehole was grouted with the previously described grout mix (no sand pack was used for this installation). Additional standard vw transducers were placed in the Casagrande piezometers to allow for automated readings. The test consisted of variable pumping of nearby deep wells and recording piezometer
response, with readings taken at 1-minute intervals. The test results confirmed that the sand pack can be eliminated without affecting quality of data. Accordingly, engineers proceeded with spring-activated vw piezometers installed in fully grouted boreholes.

![Figure 1: Response of different piezometer types to pumping](image)

Observations of the test set continued for the next several months. Measurements taken during the active dewatering phase of the project are presented on Figure 1. The data indicate that fully grouted piezometers react as fast as those installed in a sand pack. However, the vw piezometers in sand pack appear to be slightly more sensitive to fluctuations in pumping rates. Casagrande type piezometers have the longest time lag and are the least sensitive of three.

**SELECTION OF LOCATIONS**

The next step in developing the instrumentation program was selecting instrument locations. Since excavation was to be performed in discrete cells, each cell had to have at least one instrumented cross-section. Typically, the instrumented cross-section was located in the middle of the cell, where the 3-D effects of surrounding unexcavated cells are minimal and therefore the dam is the most vulnerable. Old construction drawings were used to identify features of the dam (old drains and drainage tunnels, railroad trestles left behind, etc) that could increase risk of excavation and needed special attention. Depending on the height of the dam, instruments were installed in two or three rows on the dam. The first row was placed closest to the edge of the excavation, with the second and third further upstream. Each row contained multi-level instruments installed at different depths within the embankment and foundation to evaluate local and global failure planes. Where possible, engineers placed new instruments to supplement existing ones. Such placement provides a continuity of readings and is useful for interpretation. New measurements can be compared to historical data and behavior evaluated relative to baseline conditions. Typically, inclinometers and piezometers were placed in pairs. Such placement helps to identify reasons for abnormal readings and evaluate trigger mechanisms. For example, if a piezometer indicates a sudden change in pore pressure, but nearby inclinometer is stable, it could indicate a malfunctioning dewatering component. However, if deformation is noted at the same depth where pore pressure rise
is observed, it could indicate a much more serious problem, such as a developing slide. Engineers also had to evaluate effectiveness of the dewatering program. Instruments were placed to evaluate whether pore pressure was lowered to the target levels specified by slope stability analyses and, therefore, whether it is safe to proceed with excavation. Piezometers placed near a pumping well could be too close to the tip of the cone of depression and paint an overly optimistic picture, or be too far away and miss the cone of depression altogether. Based on field pump tests, laboratory permeability tests and experience in the field, engineers determined that the best location for piezometers is within 20-150 ft of a dewatering well. To ensure that the instruments survive the construction, locations had to be carefully coordinated with the contractor. On one hand, instruments need to be close to the “action” to recognize adverse effects of the construction activity before they have a chance to develop into a global problem and, on the other hand, far enough away to avoid damage or destruction.

With 24 excavation cells and multiple rows of multi-level instruments to be installed, cost was a big factor. Dr. Peck said “the fundamental rule today should be that no instrument should be installed that is not needed to answer a specific question pertinent to the safe performance of the dam” How many instruments is enough? A total of 100 inclinometers and 130 piezometers were deployed on site. Are we installing too many? Considering the consequences of dam failure, the hard to predict behavior of the 75-year-old semi-hydraulic fill embankment, the number of unknowns, and a wide range of construction activities to be evaluated, a high number of instruments and accompanying costs were well justified. The value of avoiding a failure or delays, such as stopping to evaluate developing conditions or install additional instrumentation, to the $275 Million project made the instrumentation program cost effective.

INSTALLATION

Data obtained from an instrument is only as reliable as the care with which that instrument was installed. An instrument deployed or installed improperly will supply unreliable data and through careless drilling may even affect the stability of the Dam and on-site structures.

As mentioned, the primary instruments on site are inclinometers and vibrating-wire piezometers. These instruments were to be deployed in the existing embankment and foundation of the Saluda Dam, thus, drilling was necessary to install these subsurface instruments. As a post-1930’s construction remediation, riprap armoring was placed on the downstream slope of the Dam to layers as thick as 25 ft near the toe. Drilling through riprap is not an easy task. With so many instruments to be installed, choosing a quick drilling method was a key. Conventional top drive rotary or auger-drilling methods using air or water proved to be ineffective. The solution engineers ultimately came up with was the use of sonic drilling technology. Sonic drilling employs the use of high frequency, resonant energy to advance a drill bit into subsurface formations. The resonant energy is generated by two counter-rotating weights. When the resonant Sonic energy coincides with the natural frequency of the drill string, resonance occurs. This results in the
maximum amount of energy being delivered to the bit face, and minimizes the friction of the soil immediately adjacent to the drill string, resulting in very fast penetration rates (Ref. 10). The Sonic vibration actually liquefies the material at the face of the bit and displaces the material to the side of the hole, thus minimizing the by-product coming to the top of the hole.

As described earlier, the type of piezometer used for all installations on site was a spring-loaded low-air entry vibrating wire piezometer (Geokon 4500MLP) that presses the transducer firmly against the borehole wall (Ref. 7). Prior to installation, each piezometer was checked and calibrated based on the manufacturer supplied calibration sheets. Saturation of the piezometer is also important to be sure there is no air in the filter. All piezometers were submerged in water for no less than 24 hours prior to installation, during which the filter assembly is removed from the piezometer casing and allowed to fully saturate.

For installation of vibrating wire piezometers, boreholes were drilled with sonic drilling technology to a pre-determined depth below the phreatic surface. Most installations on site are multilevel with two or more transducers grouted in a single borehole, as shown on Figure 2a. First, all transducers, starting with the bottom one, are locked in place. A tremie tube is then used to fully grout the borehole with a cement-bentonite mix from the bottom to the top in one operation. The mix used is a standard grout mix recommended by Slope Indicator and Mikkelsen (Ref. 3) and described in detail earlier. In the field, the weight of the mix was approximately 9.5lb/gal and the viscosity, measured with a Marsh Funnel, was typically 40 sec/liter.

Inclinometers on site were installed in boreholes keyed to a depth of 2-ft into bedrock, Figure 2b. The inclinometer casing is 2.75 in. Slope Indicator ABS plastic casing with snap-together joints. After drilling the borehole and before installation of the casing, an end-cap was affixed the bottom of the inclinometer casing. The joints of the casing were sealed with duct tape to prevent grout seeping into the casing and the casing was filled with water to overcome buoyancy of the water in the borehole. Once the casing was placed fully within the borehole, the annulus between the borehole walls and inclinometer casing was fully grouted from bottom to top in one operation. The mix used in inclinometer installations is the same mix used for vibrating-wire piezometers (as described above). This method of installation produces uplift pressure on the inclinometer casing during grouting, which was overcome by loading the top of the casing at surface (the inclinometer casing is held in place with the drill rig). Restraining casing at the top can cause the casing to bend (snake) within the borehole (Ref. 2) and therefore is not recommended. The problem is more severe for deeper installations, where buoyancy
force is greater. In case of Saluda, more than 100 inclinometers with depth ranging from 18 to 158 ft were installed using this method. In general, with small diameter boreholes restricting the movement during installation, numerous instruments closely spaced, and careful reading procedures, we found the data to be of an acceptable quality. However, for some inclinometers significant snaking did occur and the casing eventually disengaged at the snapped-together joints causing a large kink to appear in the displacement plot. Data over the depth where this occurred had to be disregarded. Based on the experience, we would not recommend this installation technique and in the future would use one of the techniques suggested by Dunnicliff (Ref 2).

Successful deployment of instruments needs to be matched with a high caliber of organization in the field, office management, and reporting. Labeling instruments may be an obvious step, but without proper boring logs, site plan views, and tidy organization of instruments, quality of data could be compromised.

**NEED FOR AUTOMATION**

Suitability to automation was an important criterion in selection of instruments, especially piezometers. Several factors were considered when determining the level of automation needed:

- Excavation at the toe of the Dam going on 24/7 would produce rapidly changing site conditions;
- A large number of instruments were to be installed;
- Frequency of readings for instruments near active excavations needed to be high;
- Data reduction needed to be done in a timely manner to facilitate quick decision-making; and
- High consequences of failure.

Evaluation of the factors led to the conclusion that the monitoring system was to be as fully automated as feasibly possible. However, the more complicated the setup, the more susceptible it is to malfunctions. Therefore several redundancies and checks were built into the system to ensure its uninterrupted functioning and validity of the data. For
example, data collected automatically was routinely checked against manual readings and measurements for nearby instruments and compared to each other. Manually read observation wells are used to check nearby vibrating wire piezometers and GPS surveying is used to verify surface movement picked up by the inclinometers. Visual observations of site conditions also play a key role in data validation. An often overlooked positive aspect of automation is that the less time spent on data collection and reduction the more time is left for interpretation and visual observation. Once the desired level of automation was determined, equipment was chosen for field implementation. Reliability, ruggedness and relative simplicity were important parameters in choosing the components.

One main advantage of vibrating wire piezometers is that they are easily automated. Dataloggers supplied by Geokon, Inc. (Model MICRO-10) are used to read piezometers installed in the slope above the excavation. Piezometers are wired first to a multiplexer, basically a switchbox, which is then linked directly to the datalogger. The dataloggers are capable of reading 96 instruments (6 multiplexers x 16 instruments per multiplexer), although a maximum of 32 instruments per datalogger is used for this application. This “all eggs in one basket” approach can backfire if the dataloggers malfunction. For this reason, the dataloggers need to be rugged and reliable. An environmental box was used to shield against precipitation and a grounding rod was used for lightning protection. In addition, the dataloggers were equipped with two redundant sources of power, AC power and a solar panel-to-battery setup. The AC power was taken from a nearby utility pole while the solar panel charged a deep-cycle marine battery, which in turn charged the datalogger’s internal battery. In an unlikely event the datalogger is down for an extended period of time, manual readings can also be taken directly using multiplexers. These added levels of protection afforded engineers more confidence in the use of the dataloggers.

Data collected by the dataloggers is transmitted back to the trailer via radio link, as shown on Figure 3. The dataloggers and trailer are equipped with 2.4-Ghz spread spectrum radios. A 9-dBi corner reflector antenna at the datalogger transmits the signal to a 3-dBi omni-directional antenna at the trailer at a maximum distance of 1.5 miles. Because the datalogger has to move with excavation as it progresses along the toe, each potential location was tested for radio connectivity. Initial problems with noise on the signal were overcome by increasing the signal strength. This was done with simple measures such as raising the antenna and securing the mast.

In some cases, such as near active construction or where extra long cable lengths were needed, it was not feasible to run cable from the piezometer to the central datalogger location. Those piezometers were equipped with single-channel dataloggers (LC-1), also supplied by Geokon, Inc. Data stored in LC-1 dataloggers can be downloaded in the field with laptop computers. The LC-1 loggers have proven to be very rugged, reliable and easy to use. With the help of a wireless Cisco network that covers the face of the Dam, the LC-1 data is automatically uploaded to a shared network drive. The Cisco Aeronet® network is composed of an omni-directional antenna with coverage of the downstream
slope, access point, two bridges, and yagi (point-to-point) antenna that transmits to another yagi antenna atop the trailer, as shown on Figure 3.

Figure 3: Schematic illustration of the Automatic Data Acquisition System

Inclinometers were not nearly as feasible to automate as vibrating wire piezometers because of the scale of the project and the number of inclinometers installed. Options such as in-place inclinometers and time-domain reflectometry (TDR) were looked into but dismissed based on cost and level of accuracy needed. A standard Slope Indicator torpedo probe read manually by field technicians was chosen for inclinometer readings. With an average depth of 100 ft, a typical inclinometer reading takes 30 minutes to complete.

Although the reading process itself is not automated, data reduction in a lot of ways is. The digitilt datamate (Slope Indictor) automatically stores readings at each depth and complete datasets for future downloading. The software provided by Slope Indictor (DMMWin®) allows for immediate data retrieval and comparison. Under normal circumstances, datasets are retrieved and interpreted in the trailer at the end of the shift. Although, with a laptop computer linked to the wireless network, it is possible for a technician to complete a reading, download it, and compare it with previous readings, all while still in the field and with little extra effort. In general, such level of automation was sufficient and allowed for timely data interpretation and decision making.
DATA COLLECTION

Majority of the piezometers on site were wired to an automated system. Accordingly, data collection and reduction require little extra effort after system setup is complete. During active excavations, automated piezometer readings were taken as often as every half-hour and on average one data point was collected every two hours. However, special applications, such as pump tests and borrow area blast monitoring, warranted a reading interval of a few seconds. To maintain baseline conditions and fully evaluate dewatering effects, all piezometers not connected to the automated system were read manually with either a water level indicator (observation well, Slope Indicator) or GK-403 readout box (vibrating wire, Geokon, Inc.) at least once per week. With excavation scheduled to last at least one year, the large amount of data collected would be very difficult to manage without an efficient and reliable database.

The key attribute that was looked for in potential database programs was flexibility. Data for each of the four methods used for collecting piezometer data (datalogger, single-channel logger, water level indicator, GK-403 readout box) all needed to be in one database file with minimal time and effort needed for data input and reduction. The database must also be powerful enough to catalog large amounts of data, as close to 1 million data points have been input over the last two years. Multilogger DB® (Canary Systems) was chosen for this task (Ref. 9). It allows for customizable input features that met the needs mentioned above. All data from the dataloggers and single-channel loggers is seamlessly input into the database. As a precautionary measure, the database is backed up periodically. Data taken manually in the field still must be input by hand, but it can be placed in the same database alongside the automated data. A capable charting program is included with Multilogger DB® to simplify data interpretation and reporting. The database proved to be an indispensable and a very effective tool for the project.

During excavation, when Dam stability is most at risk, inclinometers above and surrounding an active excavation cell are read at the highest frequency - 6 datasets per day per inclinometer from as many as 18 inclinometers for any given cell. Construction progressed 24 hours a day, 7 days a week, demanding a similar monitoring schedule. In the cells where excavation was complete or has not yet begun, measurements were taken at least once a week to maintain baseline conditions and evaluate effects of other construction activities. Such a high frequency of readings and overall requirements of the monitoring program lead to an abnormally large amount of inclinometer data. Reducing and managing of inclinometer data was done with Slope Indicator’s software packages DMMWin® and DigiPro®. Both packages have proven to be reliable and customizable to our needs. However, while a very advanced and useful charting program, DigiPro® does not handle large sets of data in a manageable time frame. Periodical archiving of the data files reduced the number of data sets stored for each inclinometer and decreased the processing time to a tolerable 15-20 min per graph.

Collecting a vast amount of data and incorporating it into a database is just half of the puzzle. It is equally important to monitor and record all external factors that may
influence instrument readings. Engineers carefully tracked all construction activities and environmental conditions on site with photo journals, daily logs and reports. Coordination with personnel, who worked on the dam for many years and are familiar with site conditions, and a thorough understanding of all historical data proved to be extremely important for proper data interpretation.

CONCLUSIONS

Development of Instrumentation and Monitoring Program for Saluda Dam is a good illustration of the systematic approach to planning monitoring programs recommended by Dunnicliff (Ref.1). Proceeding through a series of the logical steps and following a carefully orchestrated thought process helped engineers address the needs of the project and design a reliable instrumentation system. Correlating data to construction activities and visual observations is fundamental to the observation approach and was essential to success of our program. The key is listening to the Dam, reading the signs, interpreting them and making recommendations based on the collected information.

REFERENCES

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