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 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. This 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.
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" (Sossenkina E., April 2004), addressed analyses and design of the remedial scheme. 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 (Peck, R.B., 1969). It emphasizes a "listening to the dam" concept of interpreting the data, correlating it with construction activities, and staying a step ahead. The second paper in the series, "Listening to the Dam" (Sossenkina E., September 2004), gave examples of this approach at work on the Saluda project. This paper illustrates the thought process for how and why certain instruments were chosen, 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 on the slope 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 monument surveying and laser lines. Data from these instruments were 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 because of previous experience with the field equipment and data interpretation software.

Deciding on the type of piezometer was more difficult. Prior to remedial construction, the dam was equipped with open standpipe (Casagrande-type) piezometers. These instruments proved to be reliable and easy to use; however, they did not fit requirements for the new installation, i.e. 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 chosen model had lightning protection, a plasma surge arrestor, built in. Long-term reliability was not a concern because the construction monitoring program was 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. Recent research suggests that a sand pack is unnecessary with vibrating wire piezometers, that is, piezometers can be simply grouted in a borehole (Mikkelsen P.E., 2003). 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 fill, were installed in one of the new boreholes. Transducers were set 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 remainder of the 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 piezometer standpipes to allow for automated readings. The test consisted of variable pumping of nearby deep wells and recording piezometer response, with readings taken at
I-minute intervals. The test results confirmed that the sand pack could be eliminated without affecting quality of data. Accordingly, engineers proceeded with spring-activated VW piezometers installed in fully grouted boreholes. 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 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 the three.

**SELECTION OF LOCATIONS**

The next step in development of 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 where the dam is 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 downstream slope above excavation. 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 the 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 check whether pore pressure was lowered to the target levels specified by slope stability analyses and, therefore, whether it would be 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 survived 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 construction 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". Engineers had to decide how many instruments were enough. A total of 100 inclinometers and 130 piezometers were deployed on site. Have we installed 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.

Inclinometers and vibrating-wire piezometers needed to be installed in the embankment fill and foundation of Saluda Dam, thus, drilling was necessary. The downstream slope of the dam is covered with riprap benches, which provide easy access for a drill rig, but pose another type of challenge. The riprap layer varies in thickness from 10 ft, at the top to as much 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 (Pro sonic Corp.). 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.

Prior to installation, each vW piezometer was checked and calibrated based on the manufacturer supplied calibration sheets. Saturation of the piezometer was important to remove air from the filter. All piezometers were submerged in water for no less than 24 hours prior to installation. During saturation the filter assembly was 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 were multilevel with two or more transducers grouted in a single borehole, as shown on Figure 2a. 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. First, all transducers, starting with the bottom one, were locked in place. A tremie tube was 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 (2003) and described in detail earlier. In the field, the weight of the mix was approximately 9.5 lb/gal and the viscosity, measured with a Marsh Funnel, was typically 40 see/liter.

Inclinometers on site were installed in boreholes keyed 2 feet into bedrock, as shown on Figure 2b. The inclinometer casing is a 2.75-inch-diameter Slope Indicator ABS plastic casing with snap-together joints. After drilling the borehole and before installation of the casing, an end-cap was affixed to 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 effects 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 the inclinometer installations was the same mix used for vibrating-wire piezometers. 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 was held in place with the drill rig). Restraining casing at the top can
cause the casing to bend (snake) within the borehole (Dunnicliff, 2000) and therefore is not recommended. The problem is more severe for deeper installations, where buoyancy force is greater. At Saluda, more than 100 inclinometers with depths ranging from 18 to 158 feet 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 (2000).

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 should 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, measurements collected automatically were routinely checked against manual readings and data from nearby instruments was crosschecked and compared to each other. Manually read observation wells were used to check nearby vibrating wire piezometers and GPS surveying was used to verify surface movement picked up by inclinometers. Visual observations of site conditions played 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) were used to read piezometers installed in the slope above the excavation. Piezometers were wired first to a multiplexer, which was 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 was used on the project. This "all eggs in one basket" approach can backfire if dataloggers malfunction. For this reason, the dataloggers need to be rugged and reliable. An environmental box was used to shield dataloggers 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 the unlikely event that a datalogger was down for an extended period of time, manual readings could also be taken directly using the multiplexers. These added levels of protection afforded engineers more confidence in the use of the dataloggers.

Readings collected by the dataloggers were transmitted back to the trailer via radio link, as shown on Figure 3. The dataloggers and the trailer were equipped with 2.4-Ghz spread spectrum radios. More specifically, a 9-dBi corner reflector antenna at the datalogger transmitted the signal to a 3-dBi omni-directional antenna at the trailer. We found that with this setup the signal could be transmitted reliably to a maximum distance of approximately 1.5 miles. Because the datalogger was to move with excavation as it progressed 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, running cables from piezometers to a central datalogger location was not practical. Those piezometers were equipped with single-channel dataloggers (LC-1), also
supplied by Geokon, Inc. Data stored in LC-I dataloggers were downloaded in the field with laptop computers. The LC-I loggers proved to be very rugged, reliable and easy to use. With the help of a wireless Cisco network, the LC-I data was automatically uploaded to a shared network drive. The Cisco Aeronet® network was composed of an omni-directional antenna with coverage of the downstream slope of the Dam, access point, two bridges, and a yagi (point-to-point) antenna that transmitted 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 took 30 minutes to complete.

Although the reading process itself was not automated, data reduction in a lot of ways was. Inclinometer readings were electronically recorded in the field by the Digitilt, DataMate readout unit and later downloaded to a computer using DMMWin software. Both products are manufactured and distributed by Slope Indicator, Inc. Under normal circumstances, datasets were retrieved and interpreted in the trailer at the end of the shift,
Although, with a laptop computer linked to the wireless network, it was 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**

The majority of piezometers on site were wired to an automated system. Accordingly, data collection and reduction required little extra effort after system setup was completed. 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 the excavation scheduled to last for more than a 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. Piezometer measurements collected with all four methods used on site (datalogger, single-channel logger, water level indicator, or GK-403 readout box) had to be located in one database file with minimal time and effort needed for data input and reduction. The database also had to be powerful enough to catalog large amounts of data, since close to 1 million data points were input over the last two years. Multilogger DB® (Canary Systems) was chosen for this task. The program was suitable for both manual and automated input of the data. Most importantly it allowed for seamless input of all data into a single database file regardless of the data acquisition method. Readings taken manually in the field needed to be entered into the database by hand, while data from the dataloggers was automatically uploaded and placed in the same database alongside the manual data. A capable charting program is included with Multilogger DB® to simplify data interpretation and reporting. As a precautionary measure, the database was backed up periodically. The database proved to be an indispensable and very effective tool for the project.

During excavation, when Dam stability was most at risk, inclinometers above and surrounding an active excavation cell were read at the highest frequency - 6 datasets per day per inclinometer from as many as 18 inclinometers for a 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 had 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 led to an unusually large amount of inclinometer data. Reducing and managing inclinometer data were done with Slope Indicator's software packages DMMWin® and DigiPro®. Both packages have proven to be reliable during construction.
monitoring. The DMMWin software can analyze data statistics, calculate checksums and correct for errors. DigiPro is useful for comparison of multiple data sets and preparing various charts.

Collecting a vast amount of data and incorporating it into a database is just half of the battle. 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 have worked on the dam for many years, were familiar with site conditions and had a thorough understanding of historical data proved to be extremely important for proper data interpretation.

CONCLUSIONS

Development of the Instrumentation and Monitoring Program for Saluda Dam is a good illustration of the systematic approach to planning monitoring programs. Proceeding through a series of logical steps and following a carefully orchestrated thought process, as recommended by Dunnicliff (1988), helped engineers address the needs of the project and design a reliable instrumentation system. The construction began in 2002 with installation of the dewatering system and launch of the Instrumentation and Monitoring Program. We are currently in the third year of the remedial construction and completion of the project is scheduled for the summer of 2005. The excavation phase lasted approximately 18 months and put the Monitoring Program through a vigorous test.

Figure 4: Pre-Construction and Current Remediation Progress

Despite the extensive subsurface explorations and numerous sophisticated analyses, engineers knew little about the dam when the project began. How would the dam react to the excavation? How much movement and pore pressure fluctuations can it tolerate? Each dam is unique; no calculations and computer-aided analyses can predict what exactly it will do when subjected to stress. Some circumstances were as designed and
anticipated, some were better than anybody could have hoped for, and some were a total surprise. Overall, the dam tolerated excavation at the toe and extensive modifications of the downstream slope better than engineers anticipated. At no time was it under serious distress. Nevertheless, in several instances instrumentation and/or visual observations exceeded the established threshold levels. In all cases instruments provided timely measurements and the established interpretation procedures enabled engineers to catch problems early on and remediate them, if necessary. Remedial measures included construction of retaining walls to support excavation, protecting slopes with filter blankets to prevent piping, and buttressing the toe to provide additional support and arrest potential movements. Aside from routine maintenance and occasional troubleshooting after heavy lightning storms, instruments and automation systems proved to be very reliable and well suited for the application. The main lesson learned from this project was - "expect the unexpected and be flexible". Threshold levels had to be revised and definition of "normal behavior" adjusted as construction progressed and engineers learned more about the dam. Correlating data to construction activities and visual observations is fundamental to the observation approach and was essential to success of our program. The key was listening to the dam, reading the signs, interpreting them and making recommendations based on the collected information.

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