International Conference on Case Histories in Geotechnical Engineering

(2013) - Seventh International Conference on Case Histories in Geotechnical Engineering

01 May 2013, 5:15 pm - 6:45 pm

Wolf Creek Dam: Instrumentation & Monitoring

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Commemorate the Legacy of Ralph B. Peck
April 29 - May 4, 2013 CHICAGO
Seventh International Conference on Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

WOLF CREEK DAM
INSTRUMENTATION & MONITORING

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ABSTRACT

Wolf Creek Dam was designed and constructed between 1932 and 1952. The approximate 1 mile long combination concrete gravity and earth fill structure is located on the Cumberland River near Jamestown, KY and stores up to six million ac-ft at the maximum flood pool storage level.

In 1967-1968, seepage in the foundation of the embankment section was evidenced by sinkholes and muddy flows identified on the downstream side of the dam and Instruments identified seepage through the dam foundation. A concrete barrier wall was constructed in 1975-1979, however dam monitoring in 2004 indicated that seepage persisted through the foundation. Currently, a new barrier wall is under construction to penetrate deeper into the foundation than the previous barrier. Additional instrumentation was installed to monitor construction and ensure the new barrier wall is effective.

The purpose of this paper is to document the history of Wolf Creek Dam, the current barrier wall construction, and the extensive instrumentation monitoring implemented throughout the project life. In addition, the paper will highlight common instrumentation data errors, their implications, and ways to identify and prevent them in future projects.

INTRODUCTION

Wolf Creek Dam, located at river mile 460.9 of the Cumberland River, near Jamestown, Kentucky, is a combination concrete gravity and earthen embankment dam totaling 5,736 ft in length. The embankment portion of the dam spans a length of 3,940 while the concrete portion spans 1,706 ft.

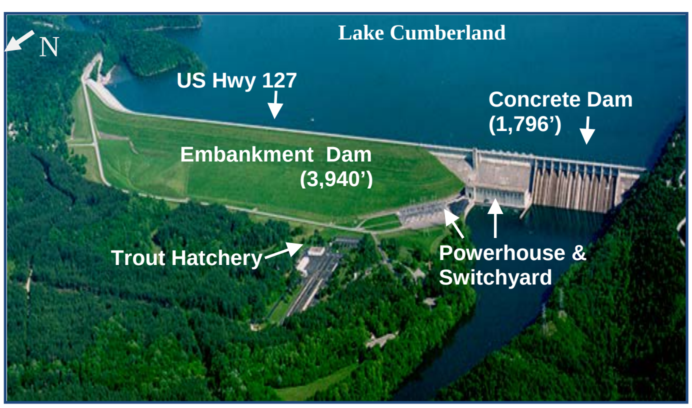

Figure 1: Aerial Photo of Wolf Creek Dam

As shown in Figure 1, the dam provides a continuous route for US Hwy 127 along its crest and contains a hydroelectric power house with six generators. With a maximum height above the lowest foundation elevation of 258 feet, Wolf Creek Dam provides storage of approximately 4 million acre-ft during normal operations and up to 6 million ac-ft during maximum flood stage.

Design of the dam and power plant began in 1938 (U.S. Army Corps of Engineers, 2005) and construction was initiated in 1941. Construction was briefly interrupted during World War II (1943-1946) before reservoir impounding began in December of 1950 and completion in 1952.

The dam embankment material generally consists of homogeneous compacted earth-fill chiefly constructed of clay, sandy clay, and clayey sands. The embankment is constructed on an alluvial layer before encountering a limestone foundation in all but a 400 ft section nearest the concrete dam interface, which was founded directly on bedrock. A seepage cutoff trench was designed and constructed along the upstream toe of the embankment. Figure 2 is a schematic a typical cross-section of the dam.

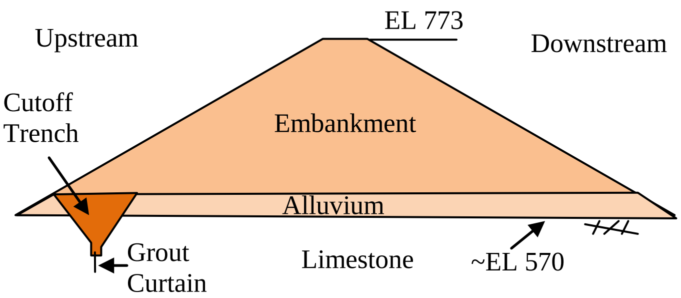

Figure 2: Schematic of typical Wolf Creek Dam Original Construction Cross-Section

The limestone foundation at Wolf Creek Dam is composed of the Ordovician Leipers and Cathys formations. During construction of the trench, a solution feature was intercepted running generally along the planned trench alignment and into the area proposed for the embankment/concrete dam interface. The existing solution feature was ultimately utilized as the cutoff trench location. The trench terminates above elevation 525 ft and has a minimum width of 10 foot at the base. A single-stage drilling and grouting operation was completed prior to backfilling operations which required a number of holes and large quantities of grout. Several large caves and numerous other solution features of varying size where documented as intercepting the trench at generally right angles. Placement and compaction of backfill clay material was often attempted on rough, vertical walls, in solution features and under rock overhangs, thus making tight compaction nearly impossible and permitting seepage paths to form through the trench.

HISTORY OF DISTRESS AND REMEDIATION EFFORTS

In 1962, wet areas were reported to be found along the toe of the dam towards the right abutment. A sink hole developed at the right abutment and was reported on August 22, 1967 near the wet areas where maintenance personnel indicated difficulty mowing. On October 7, 1967, muddy flow was reported in the power plant tailrace east of the switchyard. Two additional sink holes were discovered by project staff and were reported in the spring of 1968 just upstream of the switchyard along the toe of the embankment cone section. The first sinkhole, reported in March, 1968, developed into a 13 ft diameter hole (measured at the surface) and extended approximately 70 ft below the surface to top of rock. The second hole, reported in April, 1968, was located approximately 26 ft upstream of the first hole and was similar in size and depth (U.S. Army Corps of Engineers, 2005). These holes were indicative that the cutoff trench and grout curtain were not performing and internal erosion was progressing. At the time, there was no instrumentation installed to monitor seepage and the project relied solely on visual inspections.

The development of sinkholes led to an emergency investigation and a subsequent emergency grouting program shortly thereafter. The grouting program consisted of a three-line grout curtain that began at the embankment/concrete dam interface on the crest and extended downstream for a distance of approximately 200 ft and extending to a depth of 273 ft, targeted the base of the Leipers formation. In order to protect the downstream embankment wrap around area, additional grouting was installed perpendicular to the downstream grout lines and extending toward the right abutment and following the curve of the wraparound. In addition, single line grouting was performed at select locations near the switchyard. Figure 3 identifies the grouted areas, highlighted in red, in a 3D rendering.

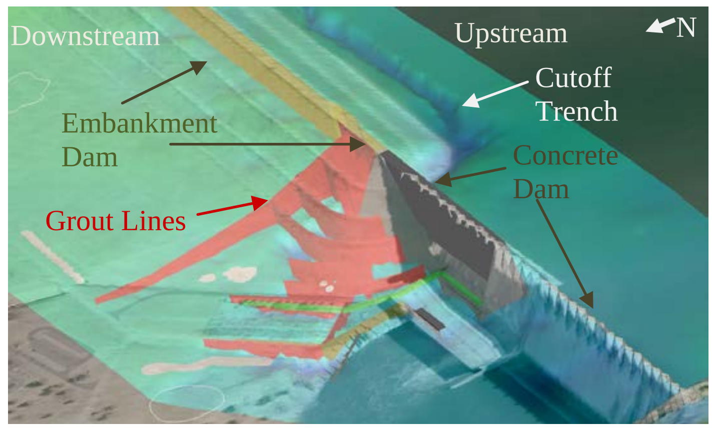

Figure 3: 3D rendering of remedial grout program (grout lines shown in red)

As part of the remedial effort, nearly 300 piezometers were installed across Wolf Creek Dam between 1968 and 1972. This was the first attempt to monitor subsurface conditions in the more critical areas of the project. Piezometers installed during this program targeted two main strata, the well developed karstic features and the epikarst found at the top of rock and embankment contact. Initially piezometers were read on a variable schedule with more critical instruments read daily and others monthly. Three PZs were located within the remedial grouting area. These instruments indicated that there was appreciable reductions in water levels recorded as the grouting program was completed; however the emergency grouting program was not viewed as a long-term solution and a more permanent solution was sought.

A board of consultants, comprised of prominent engineers and geologists including Dr. Ralph Peck, Dr. Frank Nickell, and Mr. Francis Slichter, was convened in 1972 to study alternative remedial methods and a final design was prepared to correct the seepage problems. The remedial design called for a concrete diaphragm wall extending the entire length of the embankment and below the Cathys – Leipers contact. The wall would serve as a seepage barrier by intercepting openings in the rock. The team also recommended similar measures to protect the switchyard from twenty foot fluctuations in tailwater due to the normal operation of the hydroelectric plant (Bolster, D. *et al*, 2004).

Construction of the seepage cutoff wall began in 1975 under a contract with the ICOS Corporation. The wall, commonly referred to as the ICOS Wall, consists of two separate concrete diaphragm walls, one along the dam crest, offset 16 ft upstream of the dam centerline, and the other extending from the power plant along the left perimeter of the switchyard. The design at the time was considered cutting edge technology. It consisted of telescoping primary secant elements, constructed with progressively smaller diameter casings. The diameter of the shallowest casing was 51 inches, while the diameter of the final casing, extending to the final design depth, was 26 inches. The steel casing was left in place and concrete was tremied to complete each element. Each primary element was cored to a depth of 20 to 50 ft below the bottom of the element and was then pressure tested and grouted. Secondary elements were excavated by tracked equipment between primary elements and a mud slurry was used for support of the excavation. Concrete was tremied to fill in the 4.5 ft space between primary elements.

During construction, the length and depth of the wall were reduced from the original 1972 remedial design specifications. The ICOS wall, designed to extend the entire 3,940 ft embankment length, was reduced to 2,250 ft extending from the embankment/concrete interface to the right abutment. The bottom of the wall was installed a minimum of 10 ft below the lowest indication of solution activity which, for the most part, was an elevation of 550 ft (50 ft above the Cathys-Leipers interface). The switchyard wall was installed to approximately 60 ft below top of rock.

Construction of the ICOS Wall was completed in 1979 and the previously identified wet areas began to dry. The District presented a plan to reduce the number of piezometers being monitored from over 200 to approximately 100 and to decrease reading frequency from once a week to once a month. The board of consultants concurred with the reduction in instrument monitoring and with some modifications to the piezometers that were selected.

It was expected that piezometric levels would drop downstream of the ICOS Wall post construction. However, 11 piezometers installed downstream of the ICOS Wall failed to show any significant reduction. This suggested that the remedial wall was either leaking, or did not extend far enough either in depth or in length, or a combination thereof.

Verification holes were drilled in approximately 9% of the secondary elements; less than half of these extended into rock. Data indicated that 84% of the verification holes identified segregation/honeycombing in concrete of varying degrees with more severe offenses nearest bottom of elements. Assuming that the verification holes were a representative sample of the secondary element, then 30% of the secondary elements had poor contact to rock at the base. Furthermore, there was a concern about the bond between the concrete of the secondary elements and the steel of the primary elements. Both locations were cause for concern of potential seepage paths (U.S. Army Corps of Engineers, 2005).

The lack of any appreciable reduction in pore pressure, identified potential seepage pathways, as well as the reemergence of some historic wet spots was serious cause of concern. Especially when wet areas were discovered in the vicinity of the 1968 sinkholes along the downstream toe of the embankment wrap around section. In 2001, the Nashville District contracted Fuller, Mossbarger, Scott & May Engineers, Inc. (FMSM) to conduct a study on historic piezometric data along the crest of the dam and near embankment/ concrete dam interface. The study showed an increase in piezometric levels between 5.6 and 10 ft since 1984. Piezometers located in the general area of the switchyard showed a decrease between 4 to 6 ft in piezometric level between April 1999 and August 2000. The lower piezometric levels were theorized to be the result of increase seepage through or under the switchyard diaphragm wall. Piezometric conditions directly downstream of the east end of the diaphragm wall were not found to have changed significantly. It was recommended that new piezometers be installed adjacent to the cutoff wall, on the embankment slope between the crest and the first access berm, along the toe of the concrete dam, and along the third access berm to further evaluate piezometric level and seepage gradients in the embankment and foundation.

By 2004, wet areas were extensive throughout the downstream toe and switchyard areas. Figure 4 shows a map location of the wet areas that were identified in 2004.

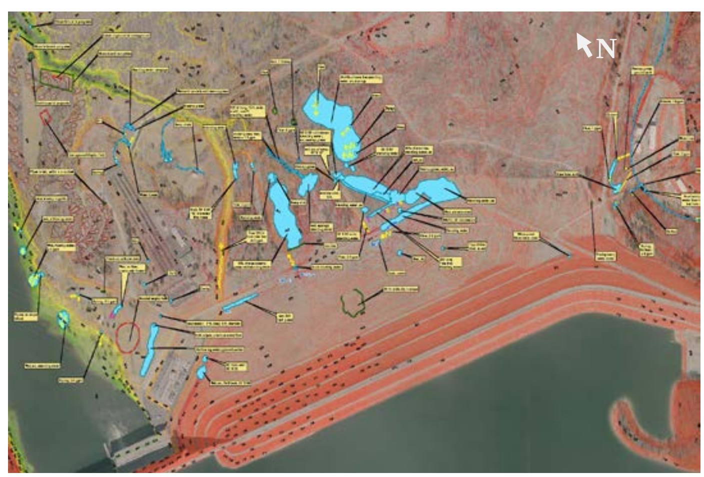

Figure 4: Plan of wet areas (shown in blue) identified in 2004

The U.S. Army Corps of Engineers, Nashville District, contracted AMEC Earth and Environmental, Inc in 2004 to complete another seepage study looking at trends in the piezometric data. The report concluded that over the last 20 years piezometers showed an approximate 10-13 ft increase in water level. The report also showed that a significant part of this increase occurred in the last four years of collected data

(2000-2004). Four of those PZs were located near the embankment/concrete dam interface. Two PZs (WA-25 and WA-29), located near the switchyard and installed at the soil/bedrock interface, indicated periods of artesian flow and responsiveness to headwater fluctuations. In addition, seven PZs, identified as rock piezometers, largely located between the dam axis and the ICOS wall, tracked headwater fluctuations closely, although there was a lag in the response noted. Rock piezometers located downstream of the dam axis exhibited relatively low piezometric levels.

CURRENT BARRIER WALL CONSTRUCTION AND VERIFICATION TECHNIQUES

In response to the visual distress signals and piezometer analyses, a new 24 in thick concrete seepage barrier wall was designed to exceed the depths of the ICOS wall and extend below the large karst features to Elevation 475 (25 ft into the Catheys formation). A double row grout curtain was incorporated into the design that extends to Elevation 425 ft (75 ft into the Catheys formation). The grouting program was iniated prior to wall construction to not only to fill voids and solution features that could potentially result in material loss during construction, but more importantly provide a thorough subsurface investigation program as construction progressed identifying rock material properties, solution feature locations, and a verification that the design wall depth was adequate. Solution features that were identified during this investigation were predominantly vertical in nature. In order to intercept these vertical openings, the grout curtain was installed in two rows of opposing 10 degree angles to maximize solution feature interception.

The grout curtain contract was completed prior to the concrete barrier wall construction contract. The two contracts were performed by separate independent contractors. In hindsight, it would have been better to have the same contractor responsible or involved in both portions of the work. Having one contractor perform both functions permits the contractor to have intimate knowledge of the project site first hand as well as to ensure that the grouting program is adequate to support the excavation and construction methods for the installation of the final barrier wall.

The current barrier wall construction began in 2008 with a scheduled completion date of late 2014. The technology of the excavation equipment and construction monitoring used for the current barrier wall far surpasses the state-of-the-art technology used 30 years ago during the construction of the ICOS Wall. The advancements to the cutter equipment and drill tooling allow for greater depths of excavation, the ability to cut higher strength and more massive materials, and maintain tool verticality at greater depths. These technological improvements are what insure minimum element overlap is achieved creating an adequate seepage barrier.

Once completed the barrier wall will form a continuous concrete seepage barrier with a minimum 24-in thickness extending the full length of the embankment dam and approximately 200 ft beyond embankment/concrete interface on the upstream side of the dam. A series of transverse elements will be keyed into the concrete monoliths to achieve a proper seal in the transition zone.

Figure 5 is a schematic of the typical cross-section of the dam and depicts the location of key construction features.

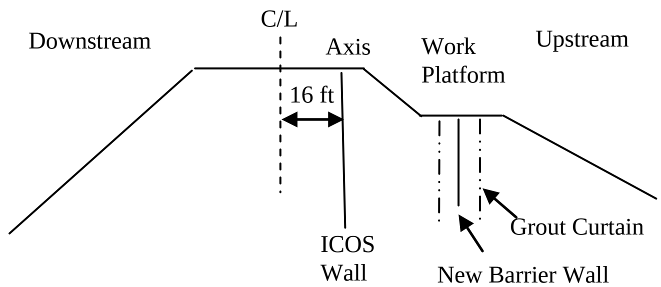

Figure 5: Typical Cross-Section of modified Dam and Key Features(NTS)

It should be noted that the axis of the dam is located 16 ft upstream of the centerline of the embankment. Until the new barrier wall contract, offsets were measured from the dam axis. The installation of the new barrier wall documents references offsets from the centerline of the dam. This inconsistency has proven to be a source of survey error when care is not taken to maintain consistent standards for referencing site Stationing and Offsets This caused some confusion and discrepancies in measurements during the current barrier wall contractor. Site stationing and offsets were provided for existing elements on the construction platform that were referenced from a previous contractor's baseline. It was assumed that the baselines were the same but after an investigation the two were significantly different especially in the curve section leading into the right abutment. The lesson learned in this error is that great care must be taken when multiple baselines have been used on a project and, when possible, new contractors should resurvey all important features of a site.

The construction of the new barrier wall began with the excavation and installation of a protective concrete embankment wall (known as the PCEW wall). The PCEW wall was composed of a low strength concrete mix installed such that it keyed into rock and isolated the embankment materials from high pressure construction activities as well as provide a homogenous low strength material of which would later be easily excavated to install the barrier wall elements. Pilot holes were drilled through the PCEW wall extending 3 ft beyond the design depth of the barrier wall. The excavation equipment used for the majority of the barrier wall elements consisted of reverse circulation drills that utilized stingers attached to the bit that guided the tool along the pilot hole. The pilot holes were drilled using a Wassarra water hammer. The steering of the drill was accomplished by incorporating slant faced bits and a bent housing. The use of steerable drilling provided a vertical guide for the excavation equipment and assisted in maintaining verticality of the final barrier wall excavation. The additional benefit that these holes provided was another opportunity to identify solution features along the excavation path not identified by borings in the grouting program. This allowed for any karstic features to be treated in order to prevent slurry loss as secant pile construction progresses. Pilot hole verticality was measured with a Paratrack and verified with a manual inclinometer after each drill run. These measurements provided the drill operator the opportunity to identify and correct vertical deviations by steering the drill back into the intended vertical alignment. The Paratrack instrument contains triaxial accelerometers and magnetometers encased in a beryllium copper pressure barrel. The instrument is inserted into the pilot hole and measures vertical alignment. The inclinometer readings required the installation of temporary inclinometer casing with bidirectional grooves that permit vertical measurement of two axes of the drill hole before manual vertical measurements could be taken with the inclinometer. Figure 6 and Figure 7 are examples of polar and elevation plots, respectively, comparing the Paratrack and inclinometer survey readings produced during construction.

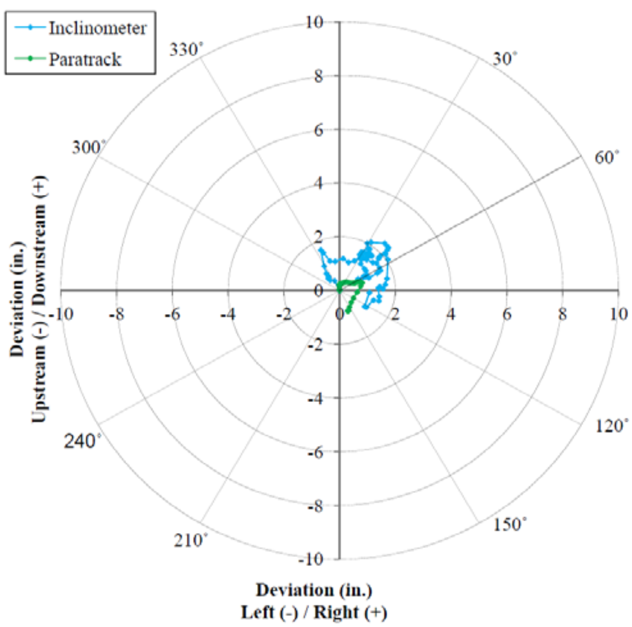

Figure 6: Polar Plot of Inclinometer (blue) and Paratrack (green) survey results

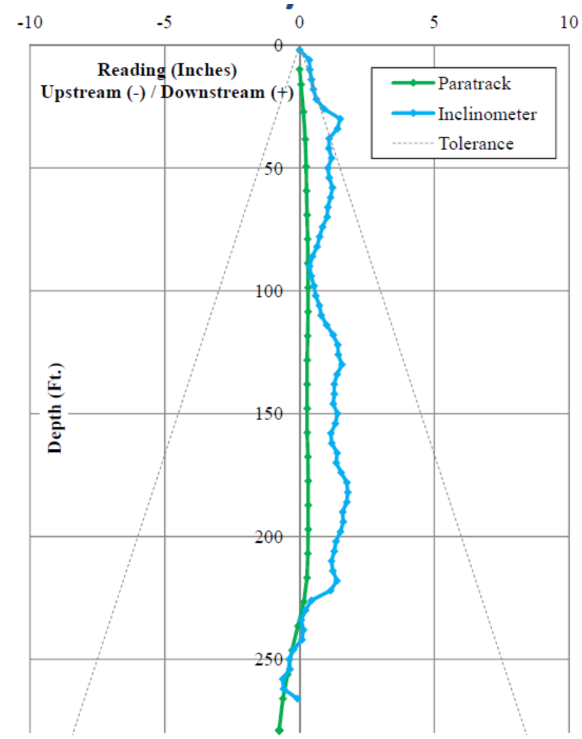

Figure 7: Elevation plot of Inclinometer (blue) and Paratrack (green) survey results

After pilot hole completion, element excavation was executed utilizing the Wirth drill, shown laying on a flatbed in Figure 8. The Wirth drill is the reverse circulation drill used to excavate elements through the PCEW wall to the final wall design depth. It is noted that a large diameter auger drill was required to pre-drill and permit the Wirth assembly to position in the pre-drill hole. The Wirth drill equipment used contains an in-house biaxial inclinometer that took four measurements at orthogonal positions as excavation progressed.

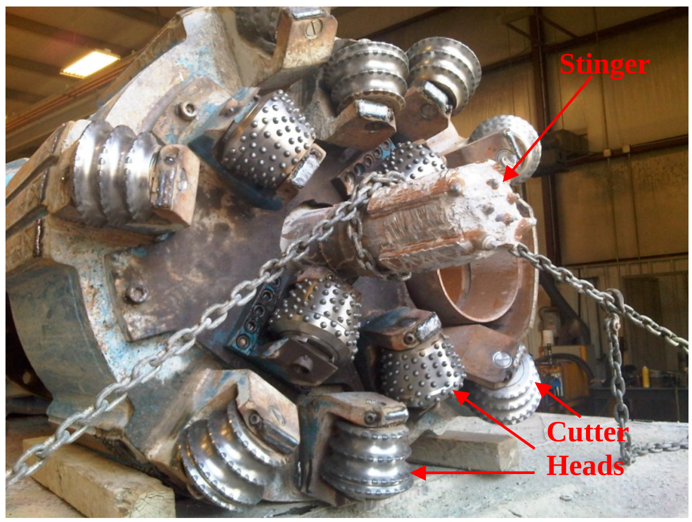

Figure 8: Wirth Drill laying on flatbed

After completion of each excavated element, verification measurements of the entire excavated depth are completed using a KODEN, which utilizes ultrasonic bidirectional echo sensing system that is used to develop element geometry. The KODEN is a continuous measurement taken from the top of the excavation. As it passes down the excavation the unit bounces sound off the walls and the sensors collects the return. The results of the Wirth drill in-house inclinometer and the Koden measurements were plotted on polar and elevation plots in similar fashion as the pilot hole verification measurements to ensure consistency of data obtained. The Koden was also key in identifying areas in the excavation where the PCEW wall may have collapse into the excavation and possibly exposed the embankment material

Excavation progressed in a series of primary and secondary elements with primary elements completed first and secondary elements installed in between two primary elements. The exact location the secondary element was determined based on the position of the primary elements to ensure that minimum overlap and wall width minimum requirements were met. Figure 9 provides a schematic of the installation series in plan view for installations composed completely of secant piles and those that were combination secant and panel elements. In the west most technique area near the right abutment the depth of excavation was shallower. In this area the contractor determined it was more economical to install a combination wall than a secant wall due to the fact that a Hydromil could be used for the shallower excavation. The depth of excavation in the remainder of the wall required the use of the Wirth drill in order to achieve the required depth. As with the Wirth drill, the Hydromill had an in-house capability to measure verticality of the excavation equipment. Panel element excavation surveys were performed in the same manner as the secant pile surveys to verify verticality of each element.

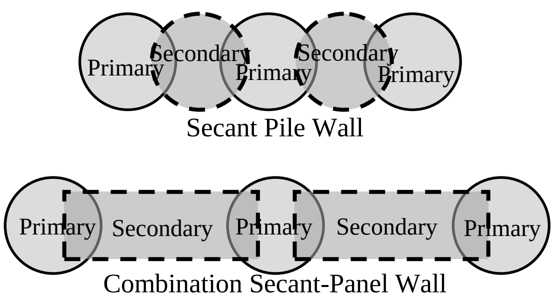

Figure 9: Plan View of Barrier Wall Construction Elements

After excavation surveys were performed and verified and prior to tremie concrete placement, samples of any material found at the base of the excavation were taken and tests were performed to ensure that less than 5 percent fines were settled at the base. The purpose of this investigation was to ensure a good contact at the rock/concrete interface at the bottom of each element of the barrier wall. Once the test was completed and criteria met, concrete was tremied into the excavation and completed to top of excavation.

Verification cores were drilled within elements and at element joints to ensure the concrete quality met minimum required construction standards. Elements or joints indicating segregation or honeycombing required remediation. Concrete dye was used on alternate elements such that the joints between two elements could clearly be identified in the verification core.

INSTRUMENTATION MONITORING

During the construction of the new barrier wall, more than 200 piezometers, 50 inclinometers, 11 extensometers, 101 surface monuments, and 32 crack pins were monitored. The number of instruments and frequency of monitoring resulted in a monitoring program that was difficult to maintain and ensure that data readings were valid.

The vast amount of instrumentation requiring manual monitoring led to the determined that in order to maintain a manageable monitoring program, select instruments would be monitored more frequently than others. To alleviate some of the manual piezometer burden an automated data acquisition system (ADAS) was implanted that included some of the more critical instruments. As part of the automation program, new installations utilizing the fully grouted piezometer method were installed in the most critical areas of the foundation. The ADAS system that was installed was set to collect data at up to 15 minute intervals across the entire embankment. The readings were then transmitted to a computer in the powerhouse where ftp servers allowed for the transmission of the data back to the District Office in Nashville. Thresholds were set such that, if exceeded, alarm signals visible on the construction platform would be triggered as well as text messages and emails sent to key personnel. A Joint Instrumentation Monitoring Plan (JIMP) was also implemented to document the roles and responsibilities of the monitoring program between the contractor and the Army Corps of Engineers Personnel and determine course of actions when thresholds were breached.

With the number of instrument measurements, whether automated or manual, numerous errors in data recordings surfaced that needed to be identified, verified, and documented. Human error was the main offender in collection of bad data; however other sources of error also impacted analysis.

<u>Human Error</u>

As manual piezometer data was analyzed, it was on frequent occasions that anomalies in the data would occur. The most frequent observed human error is transcription from the inspectors field notes to the digital forms that instrument information is submitted. These errors are easily fixed since both electoric and hard copy records are archived by instrumentation personnel, Another example of human error is when random unexplained spikes in piezometer water levels occur, such as reading water levels upstream of the cutoff wall above pool level. On several occasions, these spikes occurred on multiple instruments with no explanation. A site visit, with multiple water level readers employed to verify results, revealed that the sensitivity of the instruments was set such that humidity levels in the casing were triggering the water level reader to respond rather than actual water. On other occasions, water drops on the side of the casing were triggering the device. On one occasion, the device had algae attached near the tip and when lowered into the casing would trigger the reading device. These errors could have been avoided with proper instrument sensitivity, trained personnel having awareness of what could cause an unusually high water level reading, or with automation.

Manual inclinometers measured had similar human error issues that could have been avoided with personnel taking more care in following manufactures guidance on reading or with automation. One example of a human error that occurred frequently was inserting the inclinometer into the casing and recording the wrong axis of the bi-directional measurement. Another example is inserting the inclinometer into the casing and not permitting the instrument to acclimate to the temperature at the bottom of the casing before beginning measurements. On days when the ambient temperature is nearly 100 degrees and the instrument has been exposed to the elements for several minutes prior to insertion into a casing whose temperature at depth is 50 degrees can cause anomalous reading results. Other human error, as observed at the Wolf Creek Dam project site, included not using a pully system attached to the top of the casing that centers the inclinometer cable in the casing. The result is that field personnel taking measurements use the side of the casing to align the cable marking; this not only destroys the marking on the cable over time, making it difficult to align in the future, but also puts unnecessary pressure on the side of the instrument that the reader is pulling the cable towards.

<u>Non-Human Error</u>

Although it is stated that automated instrumentation can reduce human error, proper selection of automated instruments needs to be implemented. For example, piezometers installed using the fully grouted were not rated to withstand pressures they were subjected to during grouting activities along the embankment top of rock interface potentially damaging the instrument by over extending the diaphragm rendering the unit worthless. Lessons learned were to select instruments based on expected range of pressures not only to the natural insitu environment, but also due to project construction activities if this information is known.

Another non-human error is a response to external influences. Often, in order to ensure data is obtained at locations of interests, often instruments are installed in areas where outside influences can skew results. For example, in order to avoid damage by traffic, flush mounted piezometers were installed on the crest of the dam in line with the roadway. Traffic running over the casing covers often dislodged permitting dirt and debris, especially after precipitation events, to enter into the piezometer casing. This resulted in high readings and on occasion the complete clogging of the instrument. Rubber stoppers were installed at some locations to help prevent the infiltration of water and materials, however at a couple of locations the rubber stoppers ended up lodged within the casing preventing the ability to insert the water level reading instrument. Another example is the inclinometer casing installed on the work platform. The casing was flush mounted to avoid damage by construction equipment; however construction materials, especially after precipitation events, permitted materials to enter the casing and settle at the bottom of the casing. The result is that the bottom of the casing filled with material altering the bottom elevation of the first reading, rendering all subsequent readings at an offset and an inability to analyze changes in reading over time. In these occurrences, the casings were cleaned and re-measured, however data in the interim was not valid for use. Figure 10 is an example of data recordings after infiltration of materials into the casing.

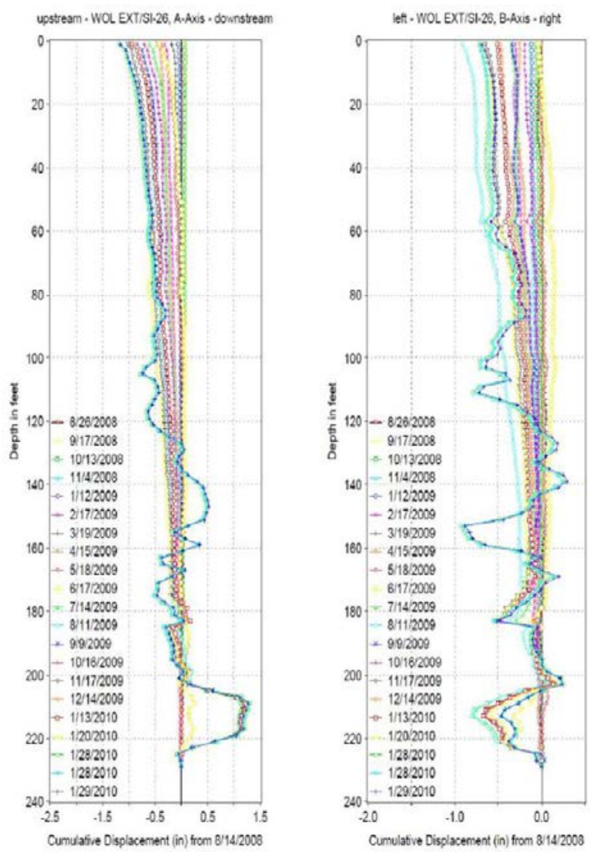

Figure 10: Inclinometer data with materials settled overtime within flush mounted casing

<u>Keys to a Successful Monitoring Program</u>

There are various components required beyond reduction in error that are recommended for a successful monitoring program. Proper instrument identification, monitoring frequency, instrument grouping and correlation, as well as dedicated instrumentation specialists and visual monitoring are all components of a successful instrumentation monitoring program.

Proper labeling of casing, cables, data logger units and components, in addition to the proper identification and verification of the location of various instruments on plan and profile drawings will greatly increase the efficiency of the program, make communication between the field and office more clear, and make trouble shooting erroneous readings far simpler.

Monitoring frequency for many projects, especially those with manual instruments, has traditional been set at a weekly or even a monthly basis. Although this may be sufficient for some projects with minimal activity and long standing history of good performance, projects that are of higher risk or are undergoing modifications require a far more frequent sampling. This is especially true the more prone an instrument is to erroneous readings. For example, if determining the displacement of a project feature based on monument surveys that are taken on a monthly basis, two consecutive bad data sets results in two months of bad data before the error is determined. Another example is when review of historical monthly PZ readings at Wolf Creek were being performed. The infrequency of the data did not provide enough of a sample set, even over several years, in order to properly correlate piezometer response to pool levels and precipitation events. It is recommended that for an in-depth analysis of dam performance and response to pool fluctuations, automated instruments collecting data at 15-minute intervals is recommended. In addition, the frequency of and timing of PZ readings should be synchronized closely with temperature and precipitation measurements as well as pool level measurements.

Further, grouping instruments based on spatial location both in plan and sensing elevation is recommended. It is helpful to use cross-section plots of grouped instruments to draw correlations between various instrument behaviors and responses to events. This is also good practice to help identify instruments which may not be functioning properly or have erroneous data sets.

In addition, a dedicated instrumentation specialist is recommended on any instrumentation monitoring program. Instrument behavior and data trends need to be clearly understood on an individual instrument basis in order to identify the differences in erroneous readings and actual events of concern.

Of course, with any good instrumentation program, visual observation is still a main requirement. Site visits and verification of instrument proper function are required to confirm what is suspected and identify areas of distress that may not be readily measured by instruments.

CONCLUSION

Wolf Creek Dam has a history of seepage concerns that were not remediated with the installation of the 1970's barrier wall due to insufficient length, depth, and possible leaks through the wall. Continued seepage led to the design requirements of a more robust wall with greater depth and extents that are able to be met based on the technological advances in excavation equipment. Instrumentation during construction of excavation equipment and verification cores were implemented to ensure wall requirements are met help to ensure that the new barrier wall will protect the dam from seepage and ultimately from failure. During the life of the dam, monitoring expanded from purely visual to a vast number of instruments both manual and automated on site. Monitoring of the dam is an important and nearly daunting task due to the vast numbers of instruments as well as the frequency of monitoring requirements. During the monitoring program, several sources of error, both human and non-human in data were identified. In addition, keys to a successful monitoring program were realized including location and identification of instruments, monitoring frequency, proper grouping and correlation of data, as well as key dedicated instrumentation specialist and continued visual monitoring.

REFERENCES

AMEC Earth and Environmental, Inc, [2004]. *Seepage Analysis, Wolf Creek Dam, Cumberland River, Jamestown, Kentucky*.

Boster, D., Franca, J., Hammer, D., Martin, J., Swartz,F., [2004]. *Board of Consultant Review Report, Wolf Creek Major Rehabilitation Evaluation Study.*

Fetzer, C. A., [1979]. "Wolf Creek Dam - Remedial Work. Engineering Concepts, Actions and Results". *Commission Internationale Des Grands Barrages*, 57-82.

Fuller, Mossbarger, Scott, and May Engineers, [2001]. *Report of Cable Tunnel Seepage Investigation, Wolf Creek Dam, Cumberland River, Kentucky.*

U. S. Army Corps of Engineers, [1952]. *Wolf Creek Dam and Reservoir Project -Cumberland River Kentucky. Volume One.*

U.S. Army Corps of Engineers, Nashville District [2005]. *Wolf Creek Dam Jamestown, Kentucky Seepage Control Major Rehabilitation Evaluation Final Report.*

U.S. Army Corps of Engineers, Nashville District, [2009]. *Wolf Creek Dam Joint Instrumentation and Monitoring Plan.*