Work underway at seepage cut-off wall for Wolf Creek Dam

COVER STORY

2013 OPA Winner: Wolf Creek Dam Rehabilitation

Wolf Creek Dam and Lake Cumberland in Russell County Kentucky is operated by the United States Army Corps of Engineers (USACE) Nashville District. It is a combination 3,940 ft long (1,200 m) non-zoned clay embankment, a maximum of 215 ft (65.5 m) above top of rock and 1,796 ft long (547 m) concrete gravity section. Built in the 1940s, the limestone beneath the embankment is characterized by an extensive interconnected network of solution features varying from fist size to large caves.

In 2005, studies conducted by the Nashville District concluded that a new seepage cut-off wall was needed as the existing cut-off wall, installed in the 1970s, did not go deep enough and did not extend laterally far enough to intercept all major karst features. The dam was classified as a "Dam Safety Action Classification I (DSAC I) – Urgent and Compelling;" the highest risk under USACE risk category rankings. Also in 2005, under a USACE risk screening program of its entire dam portfolio, Wolf Creek was classified as a Dam Safety Action Classification 1-Urgent and Compelling, which put it in the highest category. In 2007, an Independent External Peer Review from outside USACE, concluded there was compelling evidence that a piping failure mode had re-initiated and was in an "advanced continuation" stage of development.

Impounding approximately 6 million acre-ft ($7.4x10^9 m^3$) of water at flood storage, Lake Cumberland is the largest reservoir east of the Mississippi River and ninth largest in the United States. Catastrophic failure would result in widespread flooding, loss of life and economic losses in billions of dollars.

In 2008, the Nashville District partnered with a joint venture between firms Treviicos and Soletanche (TSJV) through a "Best Value" contract to construct a new seepage barrier wall. This acquisition method was used in lieu of a low bid contract due to complexity of the work and dam safety concerns. It took advantage of the experience and innovation of contractors by soliciting technical proposals that were evaluated independent of cost. Those proposals deemed technically qualified and responsive then underwent a trade-off analysis between cost and technical approach and a selection was made of the one deemed to give the best combination.

Groundbreaking methods were developed for construction and quality control. Specialized equipment designed and built for this project was used to excavate through the embankment and into the rock foundation. Dam safety and risks associated with work inside an active high head dam were at the forefront of all decision

AUTHORS *Michael F. Zoccola, P.E.,USACE and Fabio Santillan, TSJV project manager, Treviicos*

making. The Corps and contractor teams were constantly monitoring and reacting to the dam's response to construction activities. This required a robust QA/QC program and substantial upgrades to the existing instrumentation on the project.

Unprecedented Conditions

The combination of total depth, depth into limestone, and limestone hardness was unprecedented. The deepest portions of the wall are 275 ft (84 m) deep with up to 95 ft (29 m) of penetration into limestone with an average unconfined compressive strength of 14,000 psi (96 MPa). The 3,800 ft long (1,158 m) wall ties into the upstream face of the concrete monolith and runs the length of the embankment, terminating in the right abutment. The minimum required wall thickness was 2 ft (0.6 m). Grout curtains were installed upstream and downstream of the wall prior to construction to pre-treat the foundation and prevent slurry loss during installation (See Figure 1).

There were three wall element geometries used; 1) rectangular panels, 2) overlapping "secant" piles and 3) "combined wall" of panel and piles. The secant wall consists of connected sequences of primary and secondary elements with two primary elements constructed first, followed by the secondary that closes the gap.

Providing working space on a dam is always a challenge. The contractor built a 75 ft (23 m) wide work platform on the upstream face of the embankment to support the work. The platform was located upstream to avoid interference with the existing wall and to allow a major state highway across the top of the dam to remain open. Providing sufficient space for wall construction was critical for dam safety, personnel safety and operational efficiency. Additionally, to address dam safety and structural concrete concerns, restrictions were specified on the number and spacing of holes open at any time, and concrete had to reach certain strength before adjacent elements could be excavated. Thus it was a continuous challenge to sequence the equipment for various phases within the space to achieve the necessary production rates. It required the development of an intricate schedule with more than 12,500 activities.

The first wall elements installed were the Protective Concrete Encasement Wall (PCEW) panels. The PCEW's purpose was twofold. First it protected the embankment by isolating it from the follow on permanent barrier wall excavation. The TSJV proposed it as a dam safety measure to limit the amount of time the embankment was exposed to an open, slurry filled excavation while excavating the permanent wall in rock. Second, it provided a hard consistent medium through which to drill guide holes used to maintain verticality and guide permanent wall elements. The PCEW was excavated through the embankment and seated about 2 ft (0.6 m) into rock. Each element was 6 ft (1.8 m) wide by 9.2 ft (2.8 m) long. Bentonite-polymer slurry stabilized the excavation which was backfilled on completion with tremie placed concrete (See Figure 2). TSJV engineers excavated the site using a hydromill designed and built by TSJV partner Soletanche for this job. At the height of construction, 3 mills were operational. The hydromill was fitted with 3 biaxial inclinometers. These provided the operator real-time positioning data during excavation, showing actual horizontal and rotational deviations of the panel element at depth

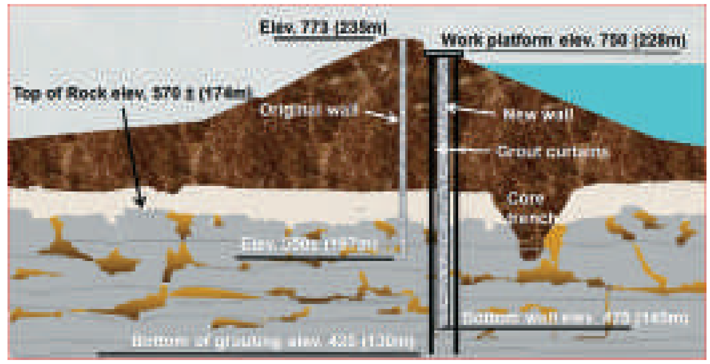

Figure 1. A generalized embankment section

from its design location. The mill could be steered by varying the rotation speed of the individual cutter wheels and tilting the wheels in a direction parallel to the wheel axes.

TSJV drilled 8 in (20.3 cm) guide holes on 35 in (88.9 cm) centers through the PCEW and into rock to 3 ft (0.9 m) below the design depth of the barrier wall. These holes were used to guide the subsequent drilling of larger secant piles. Maintaining verticality within tolerances on these holes was critical to the verticality of the barrier wall elements and their overlap and the wall thickness. These were drilled with a Wassara Water Hammer. It uses water pressure to drive a full face rock bit in a high frequency hammering action that can be used with or without rotation. TSJV was able to fit this equipment with a slant face bit or a bent housing to allow steering of the holes. Normally the bit was operated by rotating. If a hole began to deviate, the slant face and bent housing would be oriented in the hole to "steer" the hole back toward vertical and the bit operated in hammer mode without rotation. Developing the ability to steer these holes was one of the most significant advancements and critical to meeting the verticality requirement of the wall (See Figure 3). The pile barrier wall elements consisted of 1,197 overlapping 50 in (1.27 m) diameter concrete piles to form a minimum 2 ft (0.6m) thick wall. These secant piles

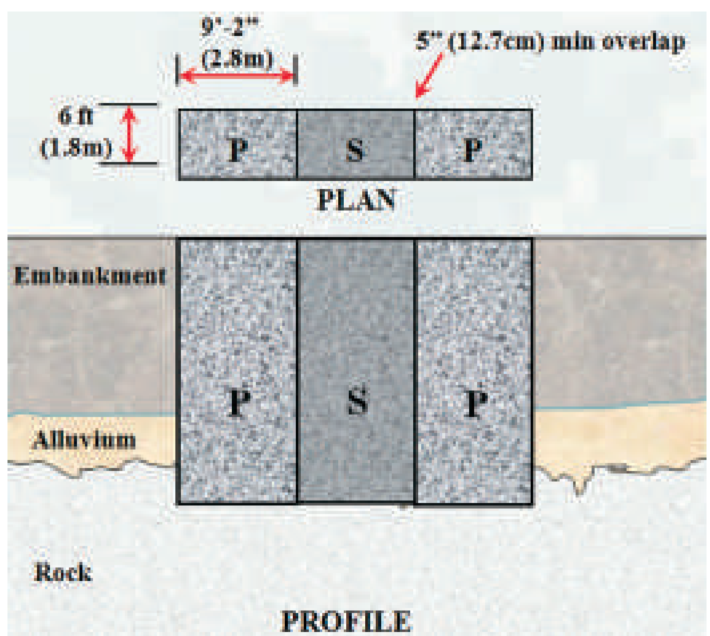

Figure 2. Schematic of the PCEW (Protective Concrete Encasement Wall)

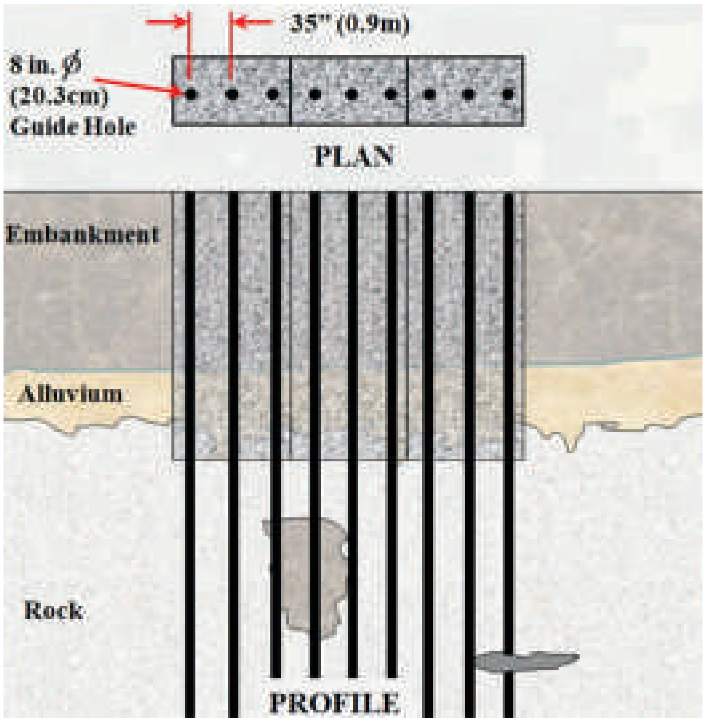

Figure 3. Schematic of the pilot holes through the PCEW

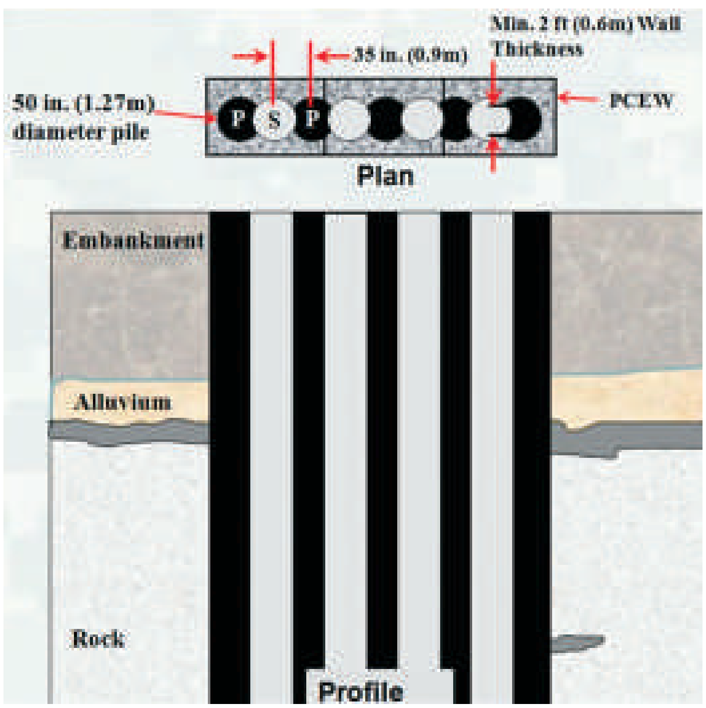

Figure 4. Schematic of this pile barrier wall

comprised 3,176 linear ft (968 m) for 84% of the total wall length (See Figure 4).

Piles were installed using a Wirth drill rig. The bottom hole assembly of the drill has a roller rock bit face that was fitted with a 2 ft (0.6 m) stinger to fit inside and follow the guide hole. The bottom hole assembly on the Wirth had on-board inclinometers that provided verticality data to the operator. The Wirth drill had no steering capability. It relied on the stinger to follow the guide hole, the 60 ft (18.3 m) long bottom-hole assembly riding inside the pile hole, and the dead weight (~ 70 tons) to maintain the location and verticality of the pile. At the height of construction, five Wirth rigs were in operation.

The combined barrier wall combined piles as primary elements connected by a secondary panel. It consisted of 50 in (1.27 m) diameter primary piles installed using the Wirth drill on each end of a 10.5 ft (3.2 m) long by 2.6 ft (0.8 m) wide secondary panel installed using the hydromill. It comprised 624 linear ft (190 m) for 16% of the total wall length.

Complex Verticality Tolerances

Arguably the most complex and untried aspect of this job was meeting installation verticality tolerances. The specifications required a "not to exceed" target tolerance of 0.25% per foot of depth. In reality, the actual allowable tolerance was dictated by the minimum wall thickness specified and the size and spacing of the wall elements selected by the contractor. To meet the minimum 2 ft (0.6 m) wall thickness, adjacent piles could deviate from their design center spacing no more than 9 in (22.9 cm) over a depth of 275 ft (83.8 m). For example, if one pile at a given depth deviated left by 3 in (7.6 cm), the adjacent pile could deviate right no more than 6 in (15.2 cm). Measurements of pile deviation at depth pushed the limits of available methods to make such measurements. Tolerances were close to the margin of error for measurement tools and means. The engineers used multiple means of measuring wall elements in space to cross check and verify continuity. For piles, two measurements were made on the guide hole during drilling. The first used a down-hole probe called the "Paratrack 2." It contained tri-axial accelerometers to obtain the inclination of the hole and its azimuth. Readings were taken every 10 ft (3 m) to determine location and whether steering was needed to bring the hole back toward vertical. The second measurement was made after the hole was completed by installing inclinometer casing in the hole and running an inclinometer survey. During the pile drilling, two additional measurements were made. One was from the Wirth's on-board inclinometer system. The other followed completion of the

The hydromill is inserted into a steel guide frame locked into guide walls on the work platform, allowing the mill to begin excavation at the right location in a vertical position

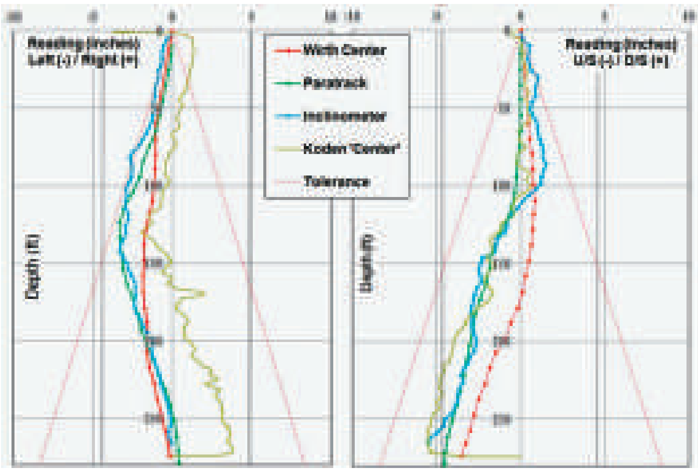

Figure 5. Comparison plots of deviation vs. depth for a real pile

pile hole using an ultrasonic echo system made by KODEN Electronics Company. It mapped the shape and vertical accuracy of the hole. Thus four independent measurements were made to determine pile verticality. Comparison plots of deviation vs. depth for the four methods on an actual pile showed the consistency achieved among the four measurements with less than about 4 in (10 cm) maximum of discrepancy among them (See Figure 5).

Of the 1,197 piles, only one pile required replacement due to its verticality being out of tolerance and two piles were replaced because of tremie concrete quality. TSJV replaced the piles by backfilling the hole with concrete and re-drilling. There were 1,196 joints totaling about 280,000 linear ft (85,344 m). Wall thickness was calculated over the depth of each joint for comparison to the required 2 ft (0.6 m) minimum. Besides the one pile replaced, at only one location was the wall thickness between adjacent piles borderline. This was at a depth of 270 ft (82 m) and the indicated thickness was 1.95 ft (0.59 m). This measurement was based on KODEN data. Other measurement methods gave a wall thickness greater than 2 ft (0.6 m). TSJV accepted this as meeting requirements. Overall, statistics showed the minimum wall thickness was the 1.95 ft (0.59 m), the maximum was 4.4 ft (1.3 m), and the average was 3.2 ft (0.98 m).

The Combined Barrier Wall sections all exceeded the required 2 ft (0.6 m). Measurement statistics showed a minimum wall thickness of 2.6 ft (0.8 m), a maximum of 3.1 ft (0.9 m), and an average of 2.6 ft (0.8 m).

These extraordinary results were due to the techniques pioneered on this job for installing, steering and measuring in real time the location of wall elements.

QC Data Management Challenge

Meeting installation tolerances was not the only daunting task that generated a lot of QC data. The grouting program was also one. Placing tremie concrete to these depths and verifying its strength, durability, soundness and permeability was another. With 200+ instruments of several types monitoring the dam's response to construction activities, instrumentation was yet another example requiring real-time analysis.

Using data in disparate formats from various storage sites was not conducive to real-time analysis and decision making nor would it allow a comprehensive, efficient and timely post-construction review. The Nashville District and TSJV collaborated to develop the Wolf Creek Information Management System (WCIMS) to handle the data and to make it usable in real time for analysis, decision making, visualization and project tracking. The system comprised a large enterprise database containing all construction data, a GIS component for data visualization and hyperlinks to PDF documents associated with all elements of the work. The final dataset includes more than 71 million records and more than 25,000 files.

On March 6, 2013, the final pile was installed nine months ahead of schedule. Without the use of WCIMS, the effort to summarize the QC data for a thorough post construction assessment would have taken many man-months. With WICMS documenting the results from the robust QC/QA program, just six days later a comprehensive review was conducted over 1.5 days by USACE dam safety professionals and outside advisers. At this meeting, conclusions were reached and decisions made without the need for additional data requests or further deliberations.

The Wirth drill being installed atop casing bolted to the work platform at surveyed locations

All parties to the project concluded a quality "state-of-the-art" wall had been built that would serve as a model for barrier wall projects within USACE. Concurrence was given to immediately begin the process of relaxing interim pool restrictions that had been in place since January 2007. Arriving at such an important decision so quickly after completion was significant. The USACE could capture spring rains and begin to restore project benefits a full season sooner. This was welcome news to the hydropower distributors, and for the surrounding communities that derive their livelihood from recreational users.