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CRITICAL INFRASTRUCTURE
PART ONE OF A SERIES

TAKE TWO

ARMY CORPS TAKES ANOTHER CRACK AT SEALING WOLF CREEK DAM'S SEEPING FOUNDATION

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CRITICAL INFRASTRUCTURE: PART ONE OF A SERIES

OUT OF SIGHT, OUT OF MIND

Visible portions of Kentucky's hydroelectric Wolf Creek Dam are in top shape, but foundation flaws make the dam a high-risk priority

By Luke Abaffy

CRITICAL INFRASTRUCTURE
PART ONE OF A SERIES

If Nashville's Grand Ole Opry House flooded with 20 feet of water, the best seats in the house would be in the balcony. That could happen if Wolf Creek Dam, near Jamestown, Ky., had a critical failure. Grand Ole Opry performers 275 miles downstream would have to be evacuated, and the estimated damages could run up to $6 billion. The risk of the dam's failure makes a $594-million remediation a top priority for the U.S. Army Corps of Engineers.

Work is now 74% complete as contractors fight seepage that is dissolving—or "solutioning"—the karst-limestone foundation under the dam. Remediation consists of building a 275-ft-deep, 3,800-ft-long concrete wall composed of secant piles and rectangular panels installed through the clay embankment and into the rock of the dam within a 5-in. tolerance. A similar smaller-scale fix was attempted in 1976. This time, the difference is in the barrier wall's greater mass and depth as well as the materials and methodology used.

Along the shores of Lake Cumberland, residents above the dam are eager to see the Corps and its primary contractor, a joint venture of Soletanche Bachy, France, and Trevi-icos, Italy, succeed. They want to see the lake—lowered in 2007 to reduce stress on the dam—return to the normal 723-ft level to revive tourism. But even with the pressure of economic need, the Corps says it cannot rush construction. "Dam safety is our top priority," says Kathleen E. Lust, the site's resident engineer for the Corps.

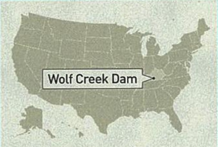
Looks Deceive

Original construction of Wolf Creek Dam finished in 1951, impounding Lake Cumberland and creating the biggest reservoir east of the Mississippi River. It holds six million acre-ft of water at ultimate capacity in flood conditions. The dam is more than a mile long and is composed of two sections: a 1,796-ft-long concrete spillway and a 3,940-ft-long compacted- clay embankment.

The concrete section contains ten 37 x 50-ft tainter gates, two non-overflow sections at each end and six low-level, 4 x 6-ft sluices. A power intake section with six penstocks feeds now-idle turbines with a combined output of 270 MW—with the potential to generate $70 million in hydroelectric power revenue annually. U.S. highway 127 traverses the top of the dam.

"The dam itself is in top condition," says Tommy Haskins, the Corps' geologist and technical manager. "They did a superior job [in 1976] on the embankment. If they hadn't done that, it would likely be gone.

"The problem here is in the limestone foundation and the depth and construction of the core, or cutoff trench," says Haskins. The trench follows a solutioning feature in the rock, he says. "The cutoff trench was not only ineffective, it serves as a conduit of seepage," says Haskins.



Nature of Damage:
Failing foundation

Cost of Fix:
$594 million

Cost of Failure:
$4 billion to $6 billion

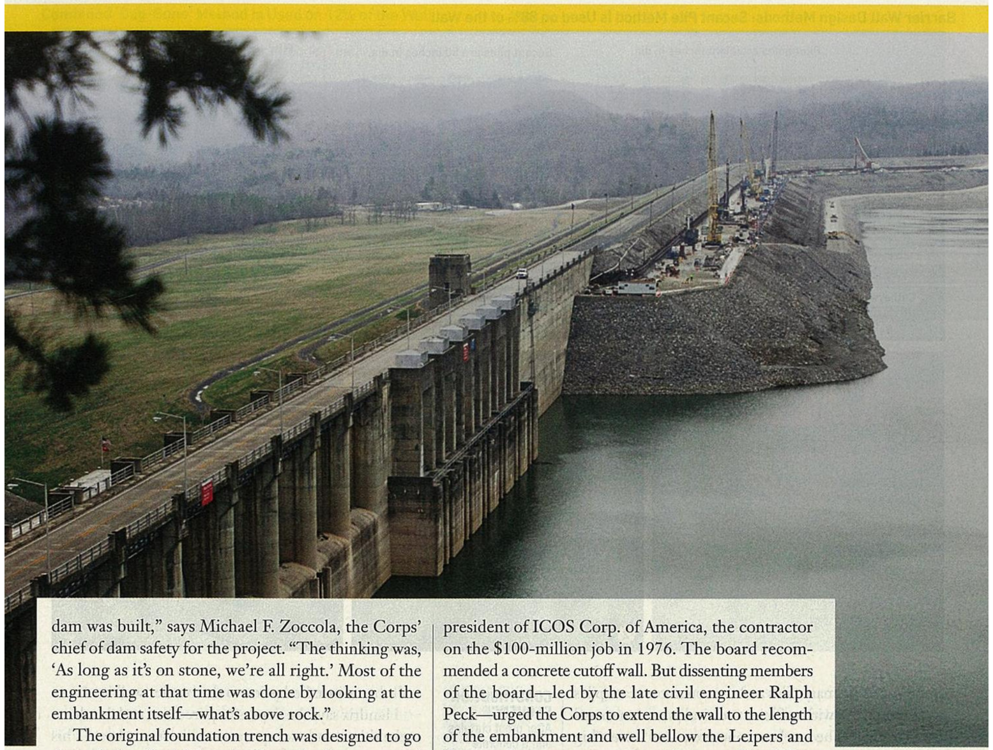
Date Action Taken: 2004

Scheduled Completion
Date: December 2013

Geological Consequences

Haskins says the embankment is unusually well built because, instead of the usual clay core burdened with coarser materials, the entire embankment is clay, which is plentiful in the area. The karst-limestone foundation is layered into what geologists call Leipers and Catheys, which are two similar limestones that can be dissolved by carbonic acid found naturally in underground water. When sandwiched together, "there is an even worse erosional surface between them," he says.

"The problem wasn't recognized when the



LIKE SARDINES The narrow platform on the lake side of Wolf Creek Dam accommodates five 85-ton, 60-ft-long Wirth drills and two hydromills.

PHOTOS COURTESY OF USACE / LEON ROBERTS

dam was built," says Michael F. Zoccola, the Corps' chief of dam safety for the project. "The thinking was, 'As long as it's on stone, we're all right.' Most of the engineering at that time was done by looking at the embankment itself—what's above rock."

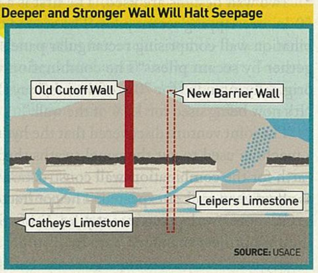
The original foundation trench was designed to go through the alluvial deposits above the limestone and 50 ft into the rock, but "they didn't go deep enough," says Haskins. "They didn't intercept all the features in the rock." Many other dams are built the same way, he adds. "You can usually get away with it," he says, "but not in the case of Wolf Creek Dam." There, a minimum 150-ft head of water is held above the foundation in which the karst limestone is solutioning. "It was terrible," Haskins says.

By 1962, significant wet areas appeared on the downstream side of the dam. Although there was no instrumentation to monitor it, by 1967, "you couldn't mow sections of the embankment, it was so wet," says Haskins. "There were cattails growing—there's a tip-off." Sinkholes followed. The Corps measured seepage and injected the limestone with grout as it began designing more permanent repairs. "In two years, we placed 290,000 cubic feet of highly pressurized grout," says Haskins. Seepage temporarily stopped.

An independent board of consultants was brought in by the Corps to evaluate the foundation and recommend action, says Arturo Ressi, who was executive vice president of ICOS Corp. of America, the contractor on the $100-million job in 1976. The board recommended a concrete cutoff wall. But dissenting members of the board—led by the late civil engineer Ralph Peck—urged the Corps to extend the wall to the length of the embankment and well bellow the Leipers and Catheys limestone contact section, says Ressi. But Peck's admonitions were not heeded, and the wall was extended from the concrete portion of the dam only two-thirds of the way from the right abutment wall, says Ressi.

David Hendrix, manager on the current project, says the Corps' 1976 decision was not cost-driven. It was a technical decision, he says. "The rock was more competent out near the right abutment," Hendrix says. The current excavation has proven that to be true. Nevertheless, less than 20 years after the wall was finished, seepage appeared on the downstream side of the dam again.

A Deeper and Stronger Wall Will Halt Seepage

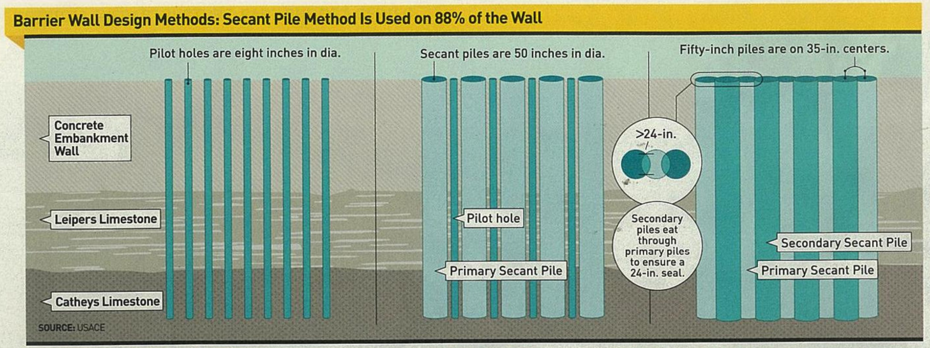


SOURCE: USACE

The Challenge

"The old wall has 26-in.-dia, steel-encased primary piles," says Lust. But the steel primary piles and the concrete secant piles were not placed with sufficient vertical precision to seal out seepage. "The steel-to-concrete joints were a big problem," adds Lust. This time around, the Corps is using a more precise method to attain a better seal.

Barrier Wall Design Methods: Secant Pile Method Is Used on 88% of the Wall



SOURCE: USACE

CONSTRUCTION SEQUENCE After grout curtains and a concrete work slab are in place, (1) the slurry-submerged hydromill eats down 2 ft into foundation rock through the clay embankment and seating; (2) concrete is poured through pipes into the slurry, forming the permanent concrete embankment wall (PCEW); (3) the PCEW lends grip and stability to 8-in. pilot holes that come within a 5-in. accuracy range, guiding pile placement.

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The new barrier wall lies upstream and parallel to the old wall but does not touch it. It maintains at least a 24-in.-thick barrier in all locations and extends 1,500 feet longer—3,800 ft in total—and deeper into the limestone than the old wall, down to a level "where there is less solutioning," says Zoccola. "Most of the wall is about 275 ft deep."

Two wall designs are used. The first is a series of 50-in. overlapping secant piles. The second is a combination wall comprising rectangular panels tied together by secant piles. "The combination wall was originally intended for 70% of the job," says Haskins. "It's now being used for 12% of the wall."

The joint venture discovered that the hydromill—a machine used to cut the panel swaths through the earth for the combination-wall construction—wasn't as effective in rock as expected. The contractor opted to use more overlapping secant piles. Fabio Santillan, the JV's project manager, says hydromills are now mostly used to excavate for a concrete embankment wall that is installed prior to the barrier wall itself.

Hendrix says the depths required and rock hardness make this foundation project unlike any other. "This is the most complicated foundation job being done in the world today," claims Santillan.

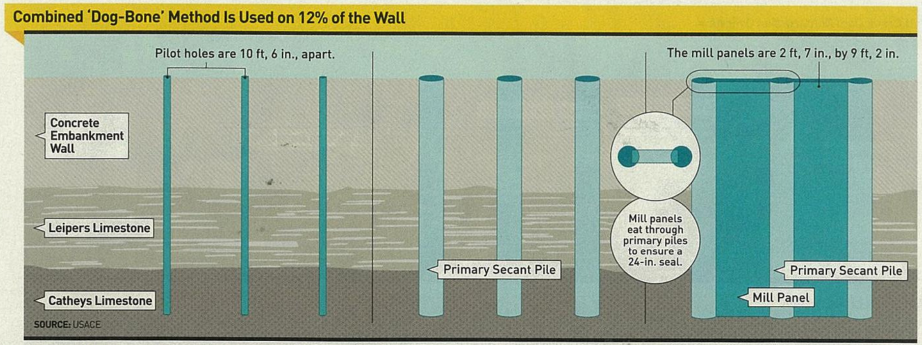
Construction of the barrier wall requires several steps of site preparation. In the $70-million first phase, grout was used to stabilize the embankment and create curtains on either side of the barrier-wall site. The curtains are formed by pressure-grouting in holes augered 12 ft on either side of the wall footprint at various intervals, depending on soil conditions. The curtains extend 50 ft below the barrier's foundation.

The hydromill, with a 6 x 9-ft-long cutter head, excavates the clay embankment, extending a minimum of two feet into bedrock, to build a protective concrete embankment wall (PCEW).

The work area is prepared for the hydromill by excavators with clamshells that produce a hole large enough to accept the machine's head. The hole is filled with a water-and-polymer slurry. The slurry keeps the cutter head cool, maintains hydrostatic pressure to hold the trench open and provides a medium for removing cuttings from the excavation, says Hendrix. The cuttings-laden slurry is cycled through pipelines

PHOTOS COURTESY OF USACE / LEON ROBERTS

Combined 'Dog-Bone' Method Is Used on 12% of the Wall



SOURCE: USACE

NEXT STEPS Fifty-four-inch augers (4) bore holes through the PCEW and rock to accommodate the (5) 50-in. reverse-circulation Wirth drill rig. The rig is equipped with inclinometers to reach precise accuracy 275 ft below ground. Finally, (6) concrete is placed through a series of 10-in. tremie pipes running to the bottom of the secant piles. The concrete displaces slurry and cuttings, floating them to the surface to be pumped away.

to a treatment area where screens, shakers and a centrifuge remove debris before cycling the cleaned mixture back into the excavation. When the hole reaches final depth, pipes are lowered in and tremie concrete is gravity-fed through the 10-in. pipes. The concrete displaces the slurry, which is recovered for re-use.

"We don't intend to jeopardize the already-strong clay embankment," says Lust. The PCEW stabilizes the clay embankment and gives a solid grip to the directional drill, which bores 8-in. pilot holes through the cured concrete as construction of the final barrier wall begins. A 54-in.-dia auger excavates 60-ft-deep holes to accommodate 50-in-dia Wirth drilling rigs, which cut into the bedrock to seat the piles of the wall foundation.

"The Wirth rig is a reverse-flow drill that operates similar to a tunnel-boring machine, only vertically," says Haskins. The business end of the drill is full of lead shot to weigh it down during drilling. The JV has five such rigs on the job.

The rigs' drilling frames are fitted with inclinometers to tell operators exactly where in the ground the frame is at any given time, says Santillan. The drill bit has a "stinger" that follows the pilot hole to a depth of 275 ft. Each rig has a small desanding plant for sifting the concrete and rock debris that is pumped out when the debris floats to the top of the slurry.

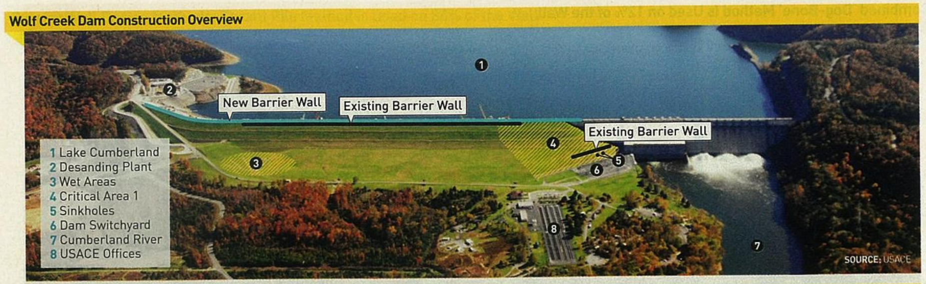
"After the drilling is complete, we verify the verticality with a Koden sonic device," says Santillan. The sonic-wave-emitting instrument's readings are used to map the exact profile and dimensions of the hole.

Haskins says the piles are set in a leapfrog pattern—primary, secondary, primary—35 in. on center, so each secondary pile overlaps the adjacent primary pile to ensure the contract's required 24-in. wall thickness in all areas. "The single most important ability we now have that they didn't have in 1970s is the ability to drill a nearly vertical hole and then go back in and measure any deviations," says Zoccola. It is difficult to maintain verticality to within five inches in 275-ft-deep holes that have to be drilled again and again, says Zoccola. He adds that the contractors' skills have been honed by the completion of 670 of the 1,138 piles required for the job.

Perfect Storm

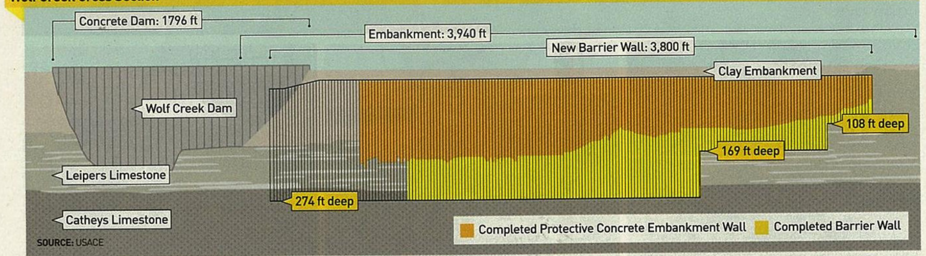
The original sequence of construction had the most unstable part of the dam—identified as "Critical Area 1" by the Corps—as one of the first areas of work. This area is where the concrete portion of the existing structure, the clay embankment and the old cutoff trench all come together, creating what Zoccola calls "the perfect storm of geologic degradation."

Wolf Creek Dam Construction Overview



SOURCE: USACE

Wolf Creek Cross Section

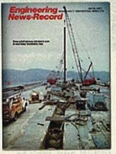


SOURCE: USACE

Soon after pressure-grouting started in the critical area, monitoring instruments detected soil movement. The Corps halted construction in the area for nine months, says Hendrix. Work was shifted to another area of the dam, and a 500-day extension was slapped on the contract—although Hendrix says this extension won't affect the projected December 2013 completion date. Gravity-grouting replaced pressure-grouting in the critical area, eventually stabilizing it to the Corps' satisfaction. During that time, the JV installed most of the rest of the barrier wall along the dam, sharpening skills now being used to tackle Critical Area 1. Santillan says the crews are at peak production now, completing up to 14 piles a week. "We have over 700,000 work hours without time lost to accident, and we're confident in our construction methods," he says.

Zoccola says that, in the old days, he would start a job, hire a contractor, finish and walk away. "Today, it's different. We're going to have to prove that we've built a good-quality wall where it needs to be. That puts the emphasis on the quality assurance," he says. QA includes reading pizometers and inclinometers, which constantly monitor the dam like the surgical patient it is. "We have a workforce of 220 to 230 people, and 20% only do [quality control]," says Santillan. In addition, the Corps has a 20-person QA team that are on-site full time checking the work as it progresses.

If instrument readings exceed set thresholds, automatic warnings are triggered, from red lights on the work platform to automatic warning messages sent to a district-office employee's Blackberry, says Zoccola. "We try to get as close to real-time, full-time monitoring as possible," he says. Geosyntec Consultants, Atlanta, developed monitoring software designed specifically to compile the project's instrument readings—for example, barrier-wall construction data, imagery, CAD plans and existing GIS files—into a geospatially accurate model of the facility. The data are available interactively to users, so they can navigate the dam site, click on features and view the associated data and reports.



TAKE ONE Construction of the first cutoff barrier wall at Wolf Creek Dam was an ENR cover story (7/22/76). The original fix tried to stop seepage using a thin concrete cutoff membrane that pierces through the clay core into rock.

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Balancing a Community

Examining the data will be key after construction is complete, as the Corps decides when it is safe to fill the lake back to design levels. The Corps is so satisfied with the method of construction, it is planning to use a similar method on the Center Hill Dam near Smithville, Tenn., Hendrix adds. But even though it is satisfied now with the means and methods, the Corps will monitor instrumentation in the dam from now on.

"We will have to react to every response we get from the structure," Haskins says, "because the one time we don't could be the one that might cause a catastrophic event." ■