

Remedial Cutoff Walls for Dams: Great Leaps and Wolf Creek

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*“The mind is not a vessel to be filled, but a fire to be ignited.”
(Plutarch c 120 AD)*

ABSTRACT

The theory is developed that advances in specialty geotechnical construction techniques are not gradual and progressive. Rather they take the form of “Great Leaps” triggered by specific project challenges. To qualify as a “Great Leap,” six successive criteria must be satisfied. The theory is tested by reference to the deep remedial cutoff recently completed at Wolf Creek Dam, KY. The theory can also be tested with reference to other techniques, such as drilling and grouting, Deep Mixing, micropiling, and anchoring. Similar validations will be explored in other papers.

1. DEVELOPMENT OF THE BASIC THEORY

Between 1858 and 1865, the great Scottish historian Thomas Carlyle wrote a 6-volume opus on the life and times of King Frederick the Great of Prussia. This work had followed his 1841 masterpiece “On Heroes, Hero-Worship and the Heroic in History.” In these publications, Carlyle developed what we now call the “Great Man” theory of history, which postulates that “the history of the world is but a biography of great men.” He evaluated the “hero” as divinity (in the form of pagan myths), as prophet (Mohammed), as poet (Dante, Shakespeare), as pastor (Martin Luther, John Knox), as man of letters (Samuel Johnson, Robbie Burns), and as king (Oliver Cromwell and Napoleon Bonaparte – paradoxically, kings in all but name). With time, at a different time, Carlyle could have doubtless explored the hero as a warrior (Admiral Lord Nelson, General Stonewall Jackson, General George Patton) or the hero as a musician (as David Bowie was in his 1975 masterpiece “Heroes”) or as patriot, like that other Bowie, of Scottish origins, Jim, who died fighting for the freedom of Texas at the Alamo in 1836.

All of us here today are engaged in some aspect of the broad field of geotechnical engineering – a discipline barely embryonic in Carlyle’s day, and bound primarily to the demands of military engineering. We can comfortably accept that the “Great Man” theory is equally valid when considering the more fundamental and theoretical branches of our discipline, such as rock and soil mechanics.

For example, Prof. Dick Goodman is widely regarded as the father of modern rock mechanics in North America. He remains a gifted engineer, thespian and tennis player. Arguably his finest and most enduring work is his 1998 book “Karl Terzaghi: The Engineer as Artist.” Prof. Goodman dedicated his book to Ralph Peck: “A courageous, strong and honest human being whose teaching, writing, speaking and practice of civil engineering continue to light the way.” Dr. Peck, in turn, is quoted in the book as follows: “Although I knew Terzaghi well [he had worked for and with him for 30 years], I did not fully appreciate the personal

struggles or the genius of the man until I read Goodman's manuscript. Goodman has caught the essence of the man." Dr. Peck gave the first Terzaghi Lecture in 1963.

Terzaghi, Peck, Goodman – not to mention others of their status such as Arthur Casagrande, Fred Kulhawy, Jim Mitchell, and Mike Duncan – typify the "Great Men" of geotechnical history, bringing enlightenment, inspiration and example to all of us they touched. Each of these men spent as much time in the field as in the classroom and each was of course intimately acquainted with construction means, methods and materials. They solved in a practical way otherwise intractable construction problems, and had the gift of communicating simply and clearly the logic and details of their solutions. None of these men, nevertheless, was a contractor. Everyone cannot be perfect.

My proposition is that in specialty geotechnical construction, the "Great Man" theory does not prevail. Instead, it is clear that the "Great Leap" theory has been at work. "Great Leap" theory, put simply, states that the technological developments in specialty geotechnical construction are not incremental, slow or progressive like the maturing of a single malt Scotch. Rather, evolution occurs in discrete and startling leaps, triggered by the demands of one special project or groups of projects. Obviously there is an integral place of honor for those behind the controls, typically entrepreneurs with the vision, courage and confidence to try new things. In this category our late friends Arturo Ressi, Alex Naudts, Wally Baker, Ken Weaver, Fernando Lizzi, Harry Schnabel, Renato Fiorotto, Clive Houlsby and Tony Barley spring to mind. Fortunately, others of this ilk remain with us, still pushing the borders and breaking the paradigms to develop new and improved equipment and processes.

To constitute a "Great Leap," I propose that six successive criteria must each be satisfied:

Criterion 1: The project, group of projects or application must be of exceptional and/or unprecedented scope, complexity and construction risk.

Criterion 2: There must exist a specialty Contractor who has the ingenuity and resources to devise the solution and there must exist a manufacturer who can design and build the equipment which is to be used.

Criterion 3: There must exist a responsible individual and/or agency on the project Owner's side who is prepared to take the perceived risk of deploying a new technology or technique on his project(s), and who already knows the answer to the tired, rhetorical question: "so where has this been used before?"

Criterion 4: The project(s) must be successful – the old adage of the operation being a success but the patient dying is indeed a fatal flaw to an aspiring "Great Leap" contender.

Criterion 5: Details of the project must have been published widely in the scientific technical press, and not just as another case history in a trade magazine, regardless of how interesting and well presented these can be.

Criterion 6: Within a few years, there must be some formal codification or other influence over construction processes, to assure the legacy of the Great Leap, and to guide and tutor future exploitations, the dubious defense of patents notwithstanding. In our field, such recognition typically comes through the publications of a Federal Agency, such as the U.S. Army Corps of Engineers, the Bureau of Reclamation, or the Federal Highway Administration; a professional society such as the Geo-Institute or ICOGs; or the efforts of a trade association such as the Association of Drilled Shaft Contractors (ADSC), the Deep Foundations Institute (DFI) or the Post-Tensioning Institute (PTI).

The "Great Leap" theory can be elegantly demonstrated by analyzing progress in a variety of specialty geotechnical construction processes such as drilling and grouting, Deep

Mixing, micropiling and anchoring. For this demonstration, I have chosen remedial cutoff walls for dams. Similar validations will be explored in other papers.

2. THE THEORY APPLIED TO REMEDIAL CUTOFF WALLS FOR DAMS

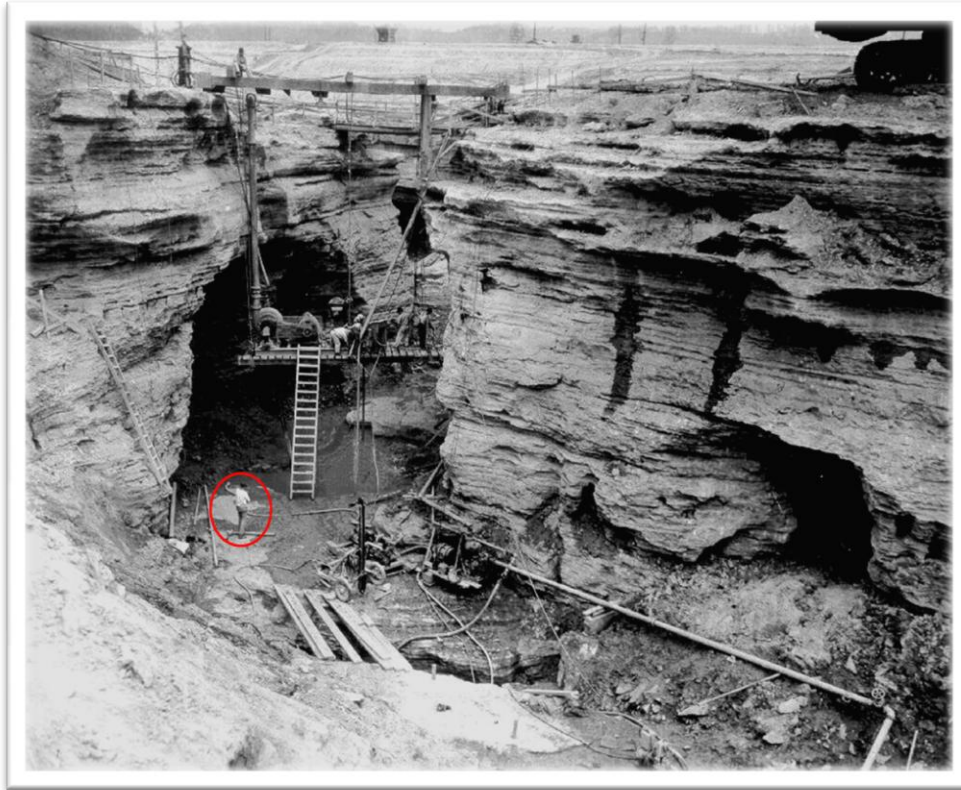
2.1 Criterion 1: The Exceptional Nature of the Project

Wolf Creek Dam, KY, comprises a 3,940-foot-long homogeneous fill embankment and a contiguous 1,796-foot-long gated overflow section (Photograph 1). Both are founded on Ordovician limestone formations with major karstification. The dam stands a maximum of 258 feet above river level and impounds Lake Cumberland, the ninth largest reservoir by volume in the U.S. and the largest east of the Mississippi. In essence, it is a 1930's design, having been authorized in 1938, and built from 1941 to 1943 and 1945 to 1952 with the three-year hiatus occurring during World War II.



Photograph 1. View of Wolf Creek Dam, KY.

Signs of hydraulic distress were noted after first impoundment and became more pronounced in the following 15 years. Only extremely intense remedial grouting programs conducted by the USACE in 1968-1970 and again in 1973-1975 saved the dam from a failure resulting from erosion and piping of the in-situ weathered material and the clay fill placed in major karstic features (Photograph 2), extending to over 75 feet below top of rock (Kellberg and Simmons, 1977; Fetzer, 1979; Simmons, 1982; and Mackey and Haskins, 2012). It was, however, recognized by the U.S. Army Corps of Engineers (USACE) and their Board of Consultants that the grouting operation was but a stopgap, given the capabilities of the grouting technologies of the period, and the certainty that potentially erodible material remained within the foundation which would continue to allow seepage to develop under the high ambient hydraulic gradient. Details of the successive phases of grouting are provided by Bruce et al. (2014).



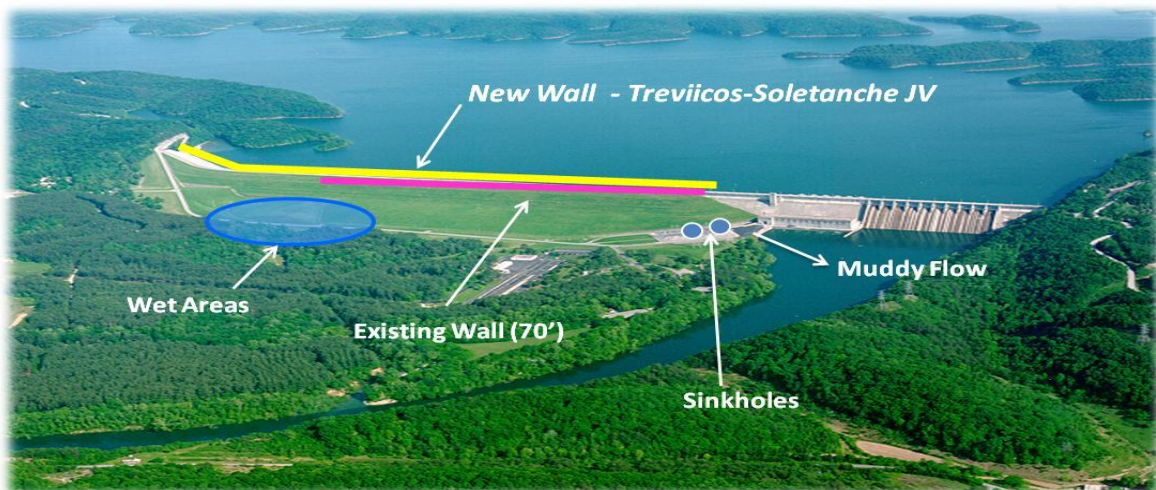
Photograph 2. Karstic features along the new cutoff wall.

A competition was arranged to encourage industry to make proposals for the “permanent” solution to the foundation problem. Seven potential techniques were proposed by various contractors, including a wide range of grouting options, and ground freezing. Only two were accepted by the USACE as being appropriate for further development. The competition was won by the ICOS Corporation of America, under the leadership of Dr. Arturo Ressi de Cervia. Their approach was to build a continuous concrete cutoff wall, from the dam crest extending about 10 feet into the foundation rock. Partly as a reflection of the mechanical capabilities of the time, and partly as a consequence of budget restraints, the main wall extended about two-thirds the embankment length, a total of 2,237 feet from the concrete section, to a maximum depth of 280 feet below the dam crest. It was nominally 24 inches thick, and comprised over 531,000 square feet, built in two consecutive phases of work. A smaller wall (600 feet long and 95 feet deep) was constructed downstream in the switchyard (Bruce, 2012). Together, the walls were built from 1975 to 1979 at a cost of around 97 million dollars (1970’s currency). This was a unique achievement, being the first example of a remedial concrete diaphragm wall installed through an existing, fully operational dam. Hitherto unprecedented levels of quality control, assurance and verification were developed and enforced (Couch and Ressi, 1979)

However, even during these original remedial works, at least one Board of Consultants Member (Dr. Peck) expressed the opinion that the cutoff would really have to penetrate deeper into rock, and to extend further along the embankment to prevent seepages eventually developing under and beyond the cutoff, such was his interpretation of the hydrogeological model. And, of course, he was proved correct.

By 2001, the typical signs of distress had begun to reemerge and, following intensive investigation, instrumentation and evaluation, the USACE declared in January, 2007, that the dam merited a Dam Safety Action Classification I (DSAC-1) status, i.e., a scenario demanding immediate intervention (“Urgent and Compelling”). The USACE therefore reduced the reservoir elevation by 80 feet below maximum capacity as an Interim Risk Reduction Measure, and planned other early interventions. An emergency remedial grouting operation was initiated in 2007 to stabilize the situation and to pretreat the rock mass prior to the construction of a second, longer and deeper cutoff wall. Incidentally, this is an excellent illustration of the “Composite Wall” Concept first described by Bruce et al. (2008), and also used on several other major USACE and TVA embankments (e.g., Mississenewa Dam, IN, Clearwater Dam, MO, Bear Creek Dam, AL, East Branch Dam, PA, and Center Hill Dam, TN.) Details are presented in a separate paper in this Conference (Bruce, 2017).

The new, minimum 24-inch-thick cutoff wall was to be built upstream and independent of the first, and to extend 1,650 feet beyond and 75 feet below the existing wall to provide 980,000 square feet of cutoff (Photograph 3) at a maximum deviation off vertical of 0.25%. Strict tolerances were specified, governing strength, permeability, homogeneity and continuity. Further practical restraints, driven by dam safety concerns, were placed on operational aspects such as the minimum allowable distance between open slurry-supported panels. The area near the concrete structure was designated the “Critical Area,” given its karstified geology, construction details and previous seepage performance characteristics. The critical nature of the overall situation demanded that time was of the essence, and a construction period of about four-and-a-half years was originally set. Further, the technical specifications had a large “Performance” element, to encourage bidders to develop innovate, responsive techniques, while at the same time assuring compliance with the extremely rigorous compliance criteria. Most importantly, the safety of the dam had to be assured during all activities, including penetration of the embankment, passing through the embankment/rock contact, and excavation into the karstic limestone foundation. It was obvious to all bidders that the technology of the 1970’s could not satisfy the numerous and greater challenges posed by the 2008 project.



Photograph 3. The location of the original and new cutoff walls, and major indicators of distress.

2.2 Criterion 2: Availability of the Technology

The original cutoff wall was built under two consecutive contracts using a clever combination of telescoped, large diameter rotary drilling (to allow the installation of 26-inch diameter steel guide pipes at 54-inch centers) followed by conventional clamshell excavation (to remove the ground between the guide pipes) using biconvex clamshells (Figure 1). Both these techniques had been used separately on other projects involving deep foundations and support of excavation by the ICOS Corporation, but never to the same depths or to such exacting standards of care or in an active dam environment. Diaphragm wall specialists from ICOS' sister companies in Europe (and particularly from Italy) were deployed in support of regular North American staff, many of whom had the construction of the diaphragm walls at the World Trade Center site in the late 1960's on their long resumé's.

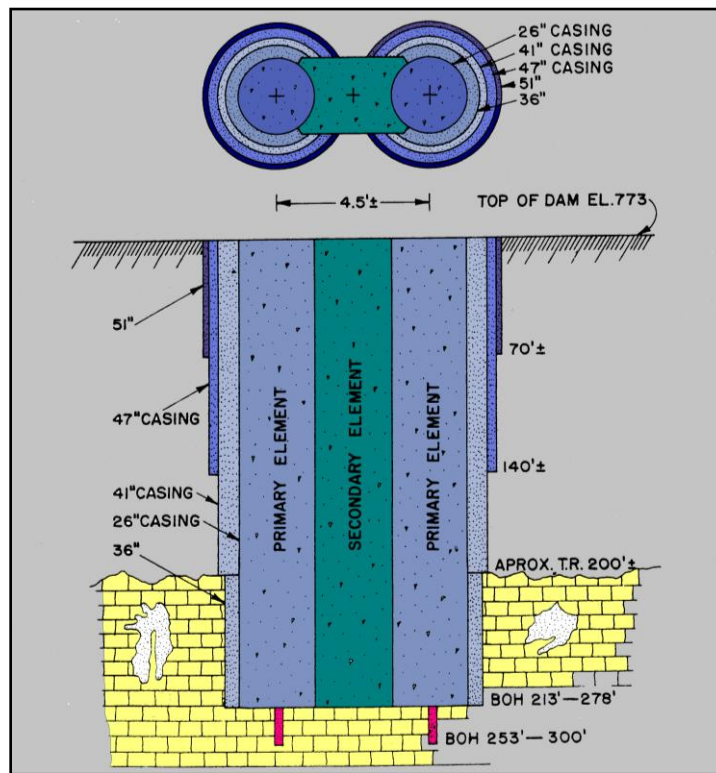


Figure 1. Schematic of construction method used in the first Wolf Creek Cutoff wall (ICOS Corp of America, Trade Literature, 1979).

Around the time of this first Wolf Creek cutoff, a technological advance of fundamental impact on diaphragm walling construction was being made in France by Soletanche, now part of the Bachy-Soletanche Group. The piece of equipment in question is termed hydrofraise by the French, and is also known as a hydromill and a cutter by other Italian and German firms who have developed their own variant. As shown in Figure 2, a hydrofraise comprises a rigid steel frame upon which are mounted cutting wheels and a powerful reverse circulation slurry pump. The hydromill is introduced into a 10- to 15-foot-deep “starter trench,” already filled with bentonite slurry, and the cutting wheels and suction pump are activated. Debris cut by the

HYDROMILL TECHNOLOGY



The core of any Hydromill is its trenching/cutting unit, that schematically consists of a heavy steel frame integrating the following components:

- swivel located on top of the frame
- two independent hydraulic engines which allows the rotation of a pair of milling drums located at the bottom of the frame;
- a mud suction pump placed just above the milling wheels;
- front and side hydraulically-operated "steering" flaps;
- a number of built-in sensors and inclinometers.

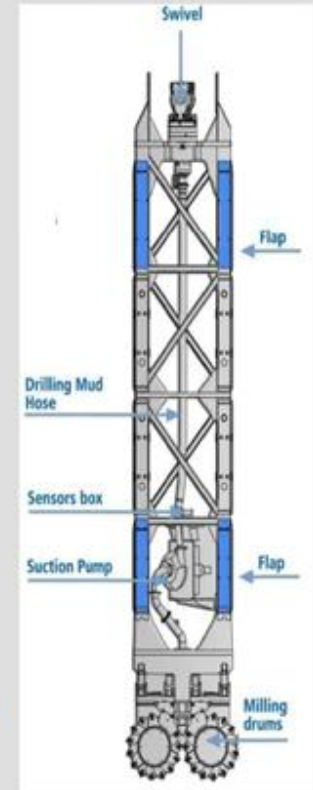


Figure 2. Schematic of a hydromill.

wheels are removed from the trench in the suspending bentonite slurry by the suction pump. The slurry is “cleaned” at surface desanding plants, and fed back into the trench, supplemented by fresh slurry, to ensure the trench remains topped up and stable. Subsequent technical developments relating to hydromills include placing hydraulically activated plates on the frame, which together with adjustments to the rotational speed and direction of the cutting wheels, permit the hydrofraise to be steered within the trench to satisfy tight verticality tolerances (< 1% depth). Typical trench widths range from 24-55 inches, but special machines have been produced to provide up to 84-inch widths. Rock of up to 20,000 psi unconfined compressive strength can be cut using appropriate teeth or picks on the cutting wheels, together with appropriate excavation techniques.

Following the application for Patent by Soletanche in 1972, the first commercial use of the hydromill was in Paris, at the Centre Français du Commerce International (Pers Coms, Richards and Jousselein, 2015). From 1973 to 1974, about 20,000 sf of load bearing barrettes were constructed, and the success led to the much larger series of projects at the Gare de Lyon, also in Paris, between 1974 and 1978. The first use of a hydromill for a new dam cutoff was at Jebba Dam, Nigeria, where in 1981 and 1982 over 364,000 sf of plastic concrete wall were

installed to depths of over 200 feet (Soletanche, 2002). This was followed by similar 24-inch thick plastic concrete cutoffs at Brombach Dam, Germany in 1983-1984, and again in 1985. These cutoffs totalled over 550,000 sf and had a reported maximum verticality deviation of only 0.13% (Soletanche, 1999). The first *remedial* dam cutoff installed with a hydromill was at the USACE's St. Stephens Dam, SC in 1984, featuring 78,000 sf of plastic concrete wall, 24-inch thick, plus 28,000 sf of soil bentonite panels. This was soon followed by the test section at the U.S. Bureau of Reclamation's Fontenelle Dam, WY in 1985, and the subsequent production work of 1987-1988, together totaling 850,000 sf of cutoff (Bruce et al., 2006). During the same period, three trial panels had been successfully installed to over 330-foot depth, near Milan, Italy, with deviations *controlled* to 0.1 to 0.6% (Bruce et al., 1989)

Thereafter, hydromills were used to wholly or largely construct similar remedial walls in 8 other U.S. dams up to 2007 (Figure 3) for a total of about 2.4 million square feet of cutoffs. Since then, further major remedial cutoffs have been constructed at several other U.S. dams, as described by Bruce (2017), while the technique as deployed by Bauer Construction was quite recently used to build a cutoff wall over 380 feet deep at the new Peribonka Dam, Quebec, (Adnan and Balian, 2008).

By the time, therefore, that bids for the second Wolf Creek project in 2008 were solicited, the original "leaps" – namely the "ICOS" method and the hydromill technique – had become common knowledge and practice in the cutoff wall industry. The problem, however, remained that the risks – technical, quality, dam safety, and schedule – posed by Wolf Creek were unprecedented. There was also the little issue of financial risk on a project, the overall cost of which was estimated at about 600 million dollars.

The solution adopted by the successful bidder – a TreviICOS-Soletanche JV – combined and leveraged the particular strengths of their respective companies:

- *TreviICOS* had been formed in Boston in 1997 when the Trevi Group, from Cesena, Italy, acquired the ICOS Corporation of America. The new company also acquired the assets of the RODIO Group, based in Casalmaggiore, Italy, and an active participant in the landmark cutoff wall constructed at W.F. George Dam, AL from 2001-2003 (Bruce, 2012). *TreviICOS*' particular corporate strengths were therefore in large diameter reverse circulation drilling using Wirth pile top equipment from Germany (Photograph 4) and conventional clamshell excavation, while more recent developments had advanced skills in directional drilling techniques, as well as with hydrofracture technology. As example, Chiarabelli and Pagliacci (2014) reported on a 800-foot-deep test panel installed at Gualdo, Italy in 2012. Adjusted by hydraulically-operated "steering flaps," the hydromill ("Tiger") was guided to within a verticality of 0.13% at the terminal depth.
- *Soletanche* were by 2008 long established as a leading specialty geotechnical contractor in North America and had acquired Nicholson Construction Company in addition to other construction assets. The company had continued to develop hydromill technology, with a focus on improving productivity and verticality control methodologies. In particular, a new generation of hydromill had recently been developed (Photograph 5) capable of efficiently and precisely excavating the 72-inch wide, 535,000 sf "Protective Embankment Concrete Wall" (PCEW) conceived to act as protection to the dam embankment and its contact, during the subsequent drilling in the underlying rock to create the secant pile cutoff (Figure 4). This "disposable"

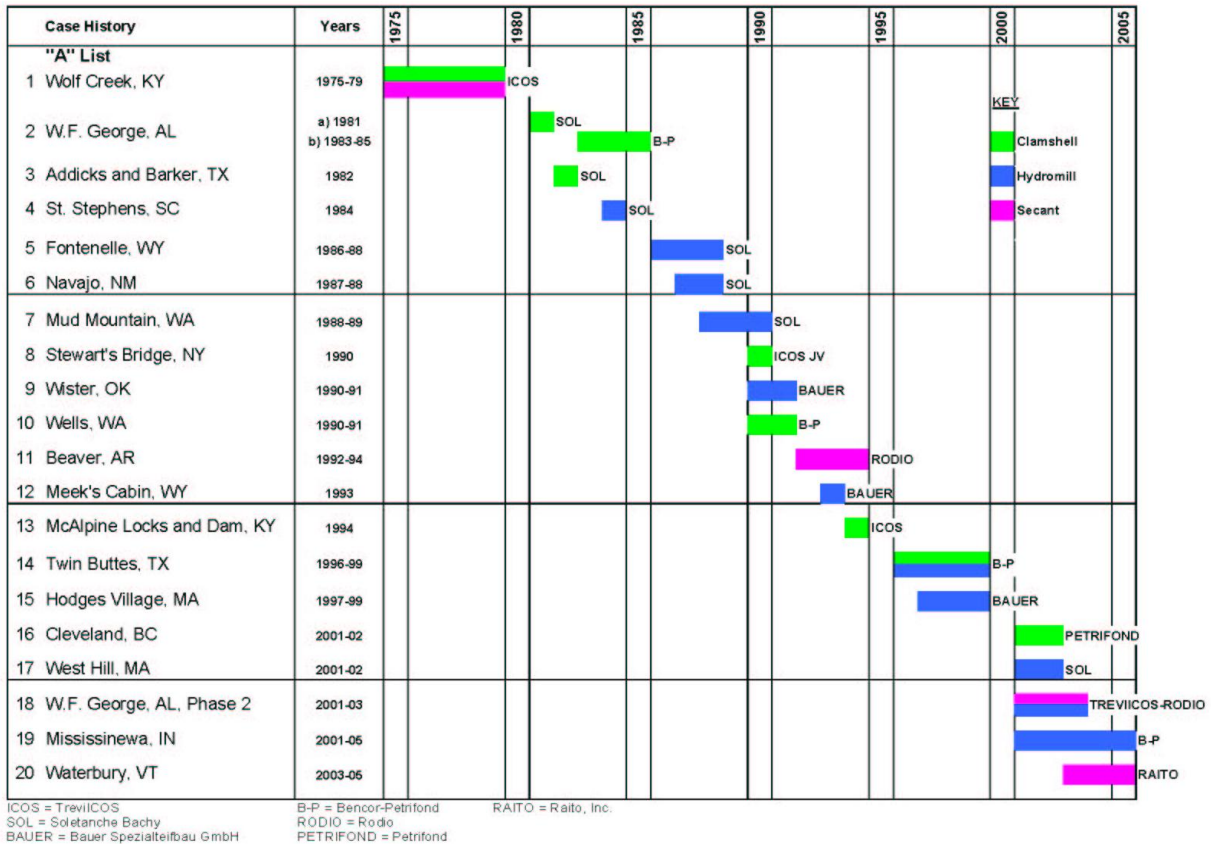


Figure 3. Project Listing showing chronology, type of cutoff and specialty contractor (Bruce et al. 2006).



Photograph 4. Wirth pile top equipment drilling secant piles.



Photograph 5. New generation hydromill excavating 72-inch wide PCEW.

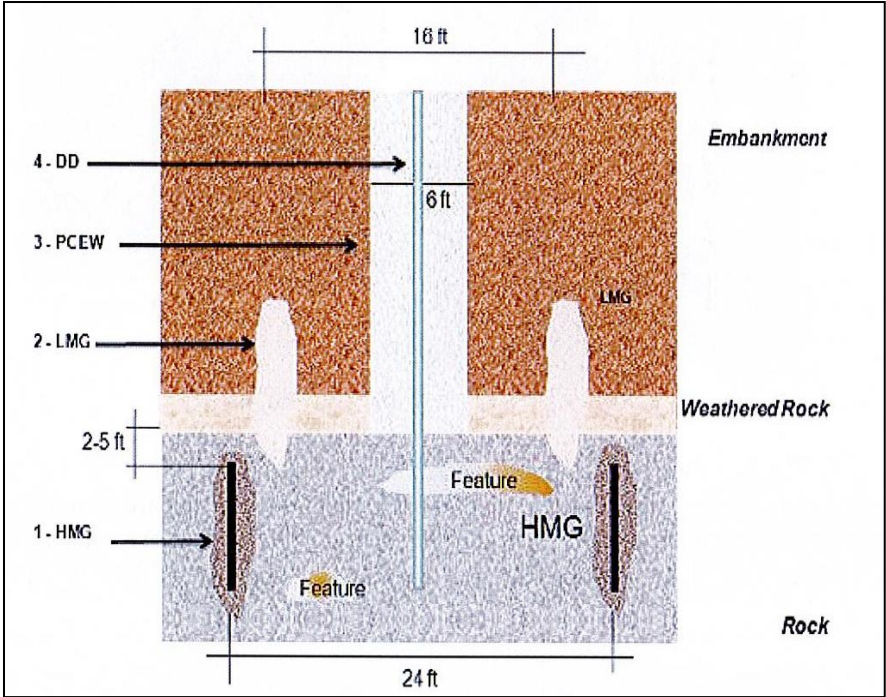


Figure 4. Preparatory phases before barrier wall construction begins, using secant piles from the Directional Drilled (DD) pilot holes (Santillan et al. 2013).

wall would therefore serve to protect the embankment from the subsequent drilling by reverse circulation drilling techniques of 1,197 secant piles of 50-inch diameter at 35-inch centers, to satisfy the minimum wall thickness criterion of 24 inches. Eight-inch diameter directionally drilled holes (using Water-Powered Down-the-Hole Hammers) were used as pilots through the PCEW and the underlying rock to guide the large diameter piles. Eighty percent of these pilot holes subsequently had deviations at 282 feet depth of less than 3 inches (Santillan, 2013).

Combining their respective skills and resources, both in-house and external, the TreviICOS-Soletanche JV was judged by the USACE to be the most responsive bidder and, as such, commenced site operations in the Fall of 2008. Integral support was provided to the JV by equipment suppliers such as Wirth and Wassara (Water-Powered Down-the-Hole Hammers) and by specialty subcontractors, principal among whom were Hayward Baker, Inc. who were responsible for the LMG investigation and treatment of the worrisome dam/foundation interface, and for completing the grout curtain in rock, which had been started in 2007 by Advanced Construction Techniques with Gannett Fleming, Inc. Extremely sensitive deviation monitoring instrumentation was specially designed and tailored for the major pieces of drilling and excavation equipment.

2.3 Criterion 3: Owner Risk Acceptance

Faced with an extremely delicate dam safety situation, the USACE and its Board of Consultants in 1975 had made an extremely courageous decision to adopt the innovative ICOS proposal. Given personal knowledge the man, it may reasonably be assumed that Arturo Ressi's persuasive engineering skills were strongly tested. However, it is hard to believe that any Board including Dr. Peck and Prof. Duncan would have condoned a method that it felt would pose unacceptable risk to the dam during construction.

The second Wolf Creek project was in many ways a significantly higher technical risk venture than the first, especially since it was conceived in a period of rapidly growing understanding and awareness of dam safety issues (and public involvement in the same), following the disasters of Hurricanes Katrina and Rita in August and September 2005. Again, it is to the immense credit of the USACE and its Consultants that the deep diaphragm wall techniques proposed by the TreviICOS-Soletanche JV were accepted, although it must be noted that the risk was mitigated by the requirement to conduct and successfully verify Demonstration Sections in areas of lowest criticality first, before work was permitted along the rest of the project.

2.4 Criterion 4: The Success of the Project

The second Wolf Creek cutoff wall employed nine different specialty construction techniques to eventually assure that the specifications in terms of verticality, strength, homogeneity, permeability and minimum thickness were met, and that the work was conducted in ways preserving the safety of the dam (Santillan et al., 2013). These nine techniques were sonic drilling, high mobility grouting, low mobility grouting, clamshell excavation, hydromill excavation, water-powered DTH directional drilling, auger/bucket drilling, reverse circulation

drilling and verification coring, most often run concurrently in a very congested site (Photograph 6). Only 1 of the 1,197 elements was found to be out of tolerance and requiring remediation, and that was installed at the beginning of the project in one of the technique Demonstration Areas. The wall was verified as otherwise conforming to the specifications, in all regards. Over 380 quality control tasks were conducted each day, and about 500,000 had been conducted by the project's conclusion (Bassola et al., 2013). The wall was completed 9.5 months ahead of the revised target date without a dam safety incident. The personnel safety record was astounding: over 1.4 million man hours worked without a lost time injury. The early observations of piezometers, and of the other traditional signs of distress, confirm the hydraulic efficiency of the wall, with the reservoir elevation fully restored.

2.5 Criterion 5: Technical Publications

In addition to numerous informational and promotional publications by the USACE and the contractor, there have been over 20 technical publications detailing various aspects of the project between 2010 and 2016. These papers have appeared in the trade and professional magazines, and also in the annual conferences of ASDSO and USSD, in the U.S., and in conferences worldwide, in association with ICOLD and DFI. Doubtless there will be further publications dealing with the medium- and long-term performance of the cutoff as more data and observations are compiled by the USACE.



Photograph 6. View of Working Platform showing very congested conditions, including two hydromills.

2.6 Criterion 6: Codification

The Risk Management Center of the USACE is currently producing an Engineering Manual on the design, construction and evaluation of cutoff walls for dams (and levees) under the guidance of David Paul. This will greatly enhance the scope of Chapter 9.4 of the existing Engineering Manual EM 1110-2-1901. The draft is currently being reviewed internally by the USACE, and externally by representatives of the DFI. The DFI Slurry Wall Committee is itself developing a guideline document relating to the selection of specialty techniques for dam and levee remediation. This document is also scheduled to appear soon. In addition, the Bureau of Reclamation is finalizing a new Design Standard on cutoff walls, under the guidance of Mark Bliss. These documents will provide support for the existing ICOLD Bulletin 150, and the European Standard EN1538.

It is also valid to note that many of the “lessons learned” during the works at Wolf Creek, were incorporated into the technical specifications for the subsequent USACE cutoff wall projects at Center Hill Dam, TN, East Branch Dam, PA and Bolivar Dam, OH. This trend *away* from Performance-type specifications towards more Prescriptive specifications, has come as a result of sharing the experiences of Wolf Creek Dam with industry at large, and is contrary to the general clamor in the industry to move *towards* Performance-type specifications. Doubtless, this technical communism will lead to more competitive bidding between the “usual suspects,” but one hopes that the extraordinary standards of performance and quality established at Wolf Creek Dam will not slip in the face of commercial pressures, on future projects.

3. FINAL REMARKS

The “Great Leap” theory postulated in this paper relies for its acceptance on six criteria to be each satisfied for the particular specialty construction technique being evaluated. The technique used as an example in this paper is remedial cutoff walls for dams. The leap was essentially a three-step: firstly the acceptance in 1975 that the basic “excavate and replace” technique was practical, feasible and safe for the first Wolf Creek Dam remediation; secondly the commercial development of the hydromill at about the same time; and thirdly the extraordinary technical advances built on these earlier methods as a result of the challenges of the second Wolf Creek Dam remediation in 2008-2013.

In consideration of the above, it is concluded that, for specialty geotechnical construction techniques, the “Great Leap” theory is sustainable from the perspective of the early Twenty-First Century. Furthermore, great leaps in all specialty geotechnical construction techniques are bound to happen one day, and we must be ready and willing to embrace them – especially those of us of more senior years.

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