THE EVOLUTION OF SPECIALTY GEOTECHNICAL CONSTRUCTION TECHNIQUES:
THE “GREAT LEAP” THEORY

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

1. DEVELOPMENT OF THE BASIC THESIS

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. This states 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, 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 wanted to be in his 1977 masterpiece) 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 be convinced 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.
There is a wonderful continuity to this argument. Prof. Dick Goodman is widely regarded as the father of modern rock mechanics. He remains a gifted engineer and thespian. 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 and Mike Duncan (The Terzaghi Award Winner in 1991) – these are the “Great Men” of geotechnical history, bringing enlightenment, inspiration and example to all of us they touched.

Now, 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 thesis 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, Dennis Millgard, Wally Baker, Fernando Lizzi, Harry Schnabel and Tony Barley spring easily and sadly 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. Many of them are recognized later in this paper.

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 died 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 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 limited number of specialty geotechnical construction processes. For this demonstration, I have chosen four processes particularly close to my experience and to my heart. I apologize to those of you whose particular field is not covered, such as ground treatment and improvement, rock anchoring (my Ph.D subject) and the wide topic of large diameter piles in all their myriad sizes and types.
“Great Leaps” are evident in these fields also and perhaps could be the subject of a companion paper by another author in the future, possibly one in the audience today.

My four illustration topics are:

1. Grout curtains in rock.
2. Cutoff walls for dams.
2. **GROUT CURTAINS**

2.1 **The Exceptional Nature of the Project**

It would be more appropriate to consider this leap as spread over a group of individual grout curtain projects between 1997 and 2007. A new understanding of the extreme risks that existed for certain dams was developed in that area. As part of the risk management actions, deep curtains were required during that period for several USACE projects, mainly for seepage remediation purposes, in limestone terrains of varying and often highly developed degrees of karstification. Only when the state of practice before this group of projects is compared with the state of practice after this group was substantially completed can the true revolution in the design and construction of grout curtains be fully appreciated.

As detailed in Weaver and Bruce (2007), rock grouting practice in the U.S. dates from at least 1893 and, according to the perspective of Verfel (1989), it achieved "a good start." Thereafter, and arguably until the late 1990’s, developments in concepts, means, methods and materials continued to occur, but at a very slow and unspectacular rate. As a consequence, U.S. practices in the 1990’s could be best described as "traditional," especially with respect to those developed and employed in Europe and Japan. During the period from 1900 to 1970, literally tens of thousands of dams were built in the U. S. (Figure 1), a high proportion of which required some form of drilling and grouting. Commonly, the grouting was thoroughly misunderstood or under-appreciated, was often unrelated to the geologic conditions, and was frequently of dubious or indeterminate benefit. In the words of Houlsby (1982), “Grouting is a mysterious operation
shrouded in all sorts of mumbo jumbo…” Many drilling and grouting programs had technical and historic value only as a site investigation tool, as opposed to a ground treatment, so low were the average grout takes.

Federal and state agencies were faced with intense staffing demands to design and inspect drilling and grouting works, and understandably relied on highly prescriptive concepts and specifications which changed little over the years. Further, they were obliged to use the low-bid system of contractor selection, a practice also governing specialty subcontractor awards. While assuring a uniformity of approach, such a high level of owner control did not encourage innovation or development by the contractors, who were basically required to act the role of suppliers and operators of equipment, and brokers of materials.

To illustrate this mentality, one may consider the opinion of James Polatty, formerly of the USACE, and a prominent grouting engineer of the period. In an invited lecture on U.S. dam grouting practices in 1974, he gave the following synopsis:

"In preparing this paper, I requested copies of current specifications for foundation grouting from several Corps of Engineers districts, the TVA and Bureau of Reclamation. In comparing these current specifications with copies of specifications that I had in my files that are 30 years old, plus my observations and experience, I concluded that we in the United States have not, in general, changed any of our approaches on grouting. AND THIS IS GOOD" (emphasis added). Interestingly, he then went on to cite "difficulty in having sufficient flexibility in the field to make necessary changes to ensure a good grouting job” as a problem on certain of his projects,
while “communications and training” was also listed as a challenge.

Features characteristic of "pre-leap" practice in the design and construction of grout curtains included:

- An almost complete absence of a rational characterization and design process, including rational completion and acceptance criteria.

- The use of vertical holes to a predetermined "rule of thumb" depth beneath the dam, regardless of the structure, lithology or permeability of the rock mass.

- The use of "single row" curtains, regardless of the height of the dam or the presence and amount of fissure infill materials.

- The use of long downstages of predetermined depth.

- The use of rotary drilling (with water flush) since percussive drilling was then synonymous with air flush which was (correctly) held to be detrimental to fissure cleanliness and so grout acceptance.

- The use of relatively low grouting pressures, controlled by rule of thumb ("one psi per foot depth"), and to a large degree practically limited by the pump type (progressive cavity) specified.
The use of "thin" grouts of excessive water:cement ratios (and so poor stability) in the mistaken belief that this would aid penetrability in the more finely fissured rock masses.

Termination of the work mainly based on grout takes as opposed to the residual permeability actually achieved in the rock mass, but also based on budget, particularly so in karstic formations where "runaway takes" could not be effectively controlled.

The use of “dipstick and gage” methods to record injection parameters.

With the unprecedented technological and dam safety challenges presented by the upcoming USACE projects, it was clear that traditional practices would be neither effective nor reliable, and new approaches would be required, from both owners and contractors.

2.2 Availability of the Technology

From the 1980’s, attempts were made by individuals and companies to introduce so-called "European" technologies into N. American practice. Put simply, the market did not adopt them, because market inertia dictated they could not be used and market demand was very low. Additionally, the technology underpinnings, although promising in concept, were limited in capabilities and insufficiently robust. A notable exception was the efforts led by the Bureau of Reclamation, supported by the USACE, in the mid-1980’s at Ridgway Dam, CO (?) and Upper Stillwater Dam, UT. However, for the reasons cited above, circumstances precluded ongoing development and adoption. Even the GIN Theory of Lombardi and Deere (1993) saw no
application in the U. S. despite widespread use in certain European and South American projects of great scale. Ironically, a further 20 years or so would pass before GIN was systematically promoted by some consultants in the U. S. market as a so-called "new technology."

However, the nature of the USACE grouting challenges conceived the invention required to satisfy them and at the forefront of this leap was Advanced Construction Techniques (ACT) Limited, a specialty contractor from Ontario, Canada. Led by individuals of knowledge and foresight, and drawing on their long experiences in ground engineering projects, ACT changed the face of drilling and grouting practices in North America between 1997 and 2007, and set the bar for other specialty contractors to reach, to the ultimate benefit of dam owners nationwide.

In considering these technological leaps, it must be acknowledged that their full potential would have been denied if not for parallel developments in curtain design and verification, and in the owner procurement policies, such as the use of "Best Value" award as opposed to "Low Bid."

These advances are comprehensively described by Wilson (2012), amongst others of the Gannett Fleming Inc. led movement. The design goal was now not to be seen to be satisfying archaic rules of thumb, but to provide an engineered structure in the ground whose fitness for purpose could be accurately and reliably demonstrated. This is the concept of the Quantitatively Engineered Grout Curtain (QEGC) propounded by Gannett Fleming’s authors (Wilson and Dreese, 2003).

So, what did ACT actually bring new to the table, *as an integrated package*, and who were their technology partners?
**Drilling.** Cubex is a Winnipeg-based but Texas-founded manufacturer of hydraulic drilling rigs with a prime focus on the underground mining market. Based on specific requirements provided by ACT, Cubex produced a next generation machine referenced as the Megamatic QXW (Photograph 1). This afforded special levels of operator control and comfort, and operational capabilities. In particular, it was configured to use the Water-Powered Down-the-Hole Hammer (WDTH) as first fully tested in the field in 1995 by LKAB Wassara, of Sweden. The advantages of the WDTH for rock fissure operations are detailed by Bruce et al. (2013), and include superior penetration rates, fissure cleaning and hole straightness (Photograph 2). This combination was first introduced at the McCook Reservoir Test Grouting Project in 2003. For overburden drilling, including the multiple long penetrations through existing embankments, the rotasonic technique of Boart Longyear (Bruce and Depres, 2004) and the double head duplex with internal auger were both introduced, satisfying the drilling requirements of the influential USACE Engineering Manual 1110-1-1807 (1997 and since updated) (Photographs 3 and 4).

The concept of automated Measurement While Drilling (MWD) had been deployed in Europe since the mid-1980’s but became, with the Cubex and Wassara combination, an integral element in drilling control (Weaver and Bruce, 2007). The concept is that every hole that is drilled in the ground, including those by “destructive” as opposed to cored methods, is a source of information on the nature of the ground. MWD provides an energy-based profile of the ground and provides vital clues as to its permeability and stability at each successive stage of a grouting project (Figure 2 and Photograph 5).
• **Injection Systems.** With consideration for the long, inclined grout holes to be water tested and grouted, ACT developed motorized “grout buggies” (Photograph 6). These not only lifted and lowered the injection lines and packers, but carried the injection parameter monitoring equipment used to relay these parameters in real time, back to “mission control.” In turn, the buggy operator could then adjust, at the hole, the rate and pressure of injection, upon instruction from the central control point. These buggies were first introduced at McCook Reservoir in 2003. Grout batching and mixing were conducted in automated grout plants (Photograph 7) the type of which had been on the market since the 1970’s.

• **Grout Materials and Mixes.** Grout mixes with high water:cement ratios (i.e., anything above 0.6 by weight) have high bleed capacities and – at least as critical – poor pressure filtration capacities. The latter parameter controls the ability of cement particles to be carried into a fissure: a grout with unacceptably high pressure filtration coefficient will have limited penetrability under pressure and will require therefore the use of very closely-spaced grout holes to give proper closure to a curtain. De Paoli et al. (1992) first published experimental information on this phenomenon as related to cohesion, and provided the seminal Figure 3. This figure illustrates how early attempts to reduce apparent cohesion by using very high water contents were then supplemented by the use of bentonite, and then other additives to produce “balanced, stable, modified grouts,” of good pressure filtration characteristics and low apparent viscosity – each vital to superior penetration capability. The importance of these findings was recognized by the Belgian grouting engineer, Alex Naudts, by then running a grouting consultancy in Toronto, Canada. His input into the late 1990’s grouting
specifications and to laboratory and field experimentations with multicomponent mixes was critical towards developing high performance High Mobility Grouts (Chuaqui and Bruce, 2003). In this regard he was greatly assisted by specialists in admixtures and additives, such as Master Builders Technologies, Inc. of Cleveland, OH. ACT and other contractors, such as Hayward Baker, Layne, and Nicholson, quickly adopted his multicomponent mix principles. ACT used these mixes first at Penn Forest Dam, PA in 1997 (Wilson and Dreese, 1998). The properties of these mixes maximize the efficiency of injection from each hole, and so permit the amount of drilling to be minimized, subject to the design requirements of the curtain.

- **Computer Control and Analysis.** A direct corollary of the deployment of grouts stable under injection pressure (i.e., having constant rheology) was that they themselves would act as test fluids, in the same way water would during a permeability test. This led Naudts to develop Apparent Lugeon Theory (1995), whereby the refusal of a stage could be carefully tracked in real time in order to bring it to a proper “refusal,” i.e., the state of minimal grout take (Figure 4). Apparent Lugeon (AL) is calculated during grout injection as:

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AL = \frac{\text{Grout Flow Rate (l/min.)} \times 10}{\text{Stage Length (m) x Pressure (bars)}} \times \frac{\text{Marsh Value Grout}}{\text{Marsh Value Water}}
\]

To exploit this theory, he developed a software package which would display, in real time, the stage pressure, flow rate and Apparent Lugeon value. He named this CAGES (Computer Aided Grouting Evaluation System), and this was first used on a major project by Gannett Fleming, for ACT, at Penn Forest Dam, PA, in 1997. Such a system could also, of course, be used for in-situ permeability testing, using water. During this project, a USACE workshop
was held at site to introduce the technology and its benefits. Subsequently, CAGES, with a variety of custom output enhancements developed by Gannett Fleming, was used by ACT and Gannett Fleming at the USACE’s Patoka Lake Dam, IN, in 2000. This project marked the first use of balanced, stable grouts, computer monitoring and Best Value Selection for Grouting, by the USACE.

At approximately the time Patoka was being brought to successful completion, ACT and Gannett Fleming introduced and first utilized their “IntelliGrout” system at Hunting Run Dam in Spotsylvania County, VA. IntelliGrout was designed as a comprehensive grouting system to automatically collect, record, analyze, and report all information required by the designer, contractor, construction manager, and owner, all in real-time. The system allowed evaluation of grouting results as they are being obtained, verification of design performance requirements, effective communication within the project team, and enabling real-time, sound engineering decisions to be made regarding program modifications to efficiently and effectively accommodate the geologic conditions. A guiding principle in the development of IntelliGrout was that it needed to be capable of converting what historically had been mountains of nearly indecipherable data into simple, visual, real-time displays that could be completely understood by technical and non-technical stakeholders and decision makers.

The application of IntelliGrout at Hunting Run Dam was a complete success, and shortly thereafter, it was subsequently utilized at multiple USACE projects including Mississinewa Dam (2003), McCook Reservoir Test Grout Program (2003), Clearwater Dam (2004), Wolf Creek Dam (2007), and Center Hill Dam (2008).
Since then, other systems have been developed, such as I-Grout (Hayward Baker), Grout-IT (Nicholson), and the advanced CAGES system as used by several contractors, in agreement with ECO Grouting Specialists, Ltd.

The use of such computer control systems has been demonstrated to improve quality and reliability, reduce project costs, and to permit the use of higher pressures with proven safety.

**Verification.** The IntelliGrout approach revolutionized the gathering, control, analysis and presentation of injection data: grouting programs were controllable and results could be engineered. An extra dimension to the evaluation of the effect of grouting was introduced by ACT at the McCook Reservoir Test program in 2003 in the form of digital borehole imaging, using the Robertson Geologger (Photograph 9). This instrument basically provided “flat core” being a sideways looking system (Photograph 10). It could be deployed in percussion drilled Verification Holes and so, at a stroke, eliminated the need for coring such holes to – hopefully – demonstrate the in-situ penetration of the grouts.

Each of these technology enhancements had been introduced at different times in different projects in the period 1997-2003. Thereafter, in the major USACE works at Mississinewa Dam, IN, Clearwater Dam, MO, Wolf Creek Dam, KY, Center Hill Dam, TN, McCook Reservoir, IL and Thornton Reservoir, IL, the progress was fully and integrally exploited by ACT and later by the other contractors. The impact was also felt in similar projects for TVA and the California Department of Water Resources.
2.3 Owner Risk Acceptance

At Penn Forest, PA, and at the Huntington Run Dam, VA, the primary risk taker was Gannett Fleming Inc., the Engineer of Record for the City of Bethlehem, PA, and the County of Spotsylvania, VA, respectively. In the case of Penn Forrest, their risk was to accept the “new technologies” in the second phase of a project in which the first phase had been conducted (acceptably) with traditional methods (Wilson and Dreese, 1998) and to do so against vocal objections and warnings of failure by many contractors. In the case of Hunting Run Dam, their risk was being responsible for ensuring field success with a completely new, complicated and unproven system. Additionally, at both projects, residual seepage rates were critical issues. Gannett Fleming took the unprecedented step of designing the grouting program to produce specific maximum residual rates, using the technology to verify during construction that performance would meet the design requirements, and subsequently monitoring performance to verify that the design requirements were, in fact, fully achieved. Risk assuaged, they and ACT relied upon the openness of USACE, primarily the Louisville, Little Rock, Nashville and Chicago Districts, in their acceptance of the new leaps. Personnel in these Districts had sufficient trust in their independent consultants to allow the “new” specifications to be used as the basis for contractor procurement. Their convictions were strengthened by a string of excellent performances and by strategic support from Headquarters, especially in the worrisome days after the New Orleans disaster in August, 2005.

2.4 Success of Project
These new approaches were used in two distinct applications for grout curtains: a) as a barrier in itself, and b) as part of a “composite cutoff” wherein the grouting is used to facilitate and expand the construction of a concrete diaphragm wall (Bruce et al., 2008). As further detailed in Bruce (2012), each of these projects conducted with the new technologies and concepts, for several agencies, has been completely successful. Curtains have been designed, constructed and verified to required residual permeabilities (5 Lu or less) and/or have permitted diaphragm walls to be installed without the feared potentially catastrophic loss of slurry that was first encountered during the test program at Mississenewa Dam, IN in 2002. In contrast, on certain projects where the “traditional” methods have still been imposed, the same “traditional” problems have arisen, specifically the inability to satisfy the target residual permeability without having to drill holes at spacings so close that they are technically unfeasible and economically unsustainable.

### 2.5 Technical Publications

The prime sources of technical papers are the Proceedings of the International Conferences held in New Orleans, LA in 2003 and 2012, and the Proceedings of the Annual Conferences held by the United States Society on Dams (USSD) and the Association of State Dam Safety Officials (ASDSO). Textbooks on the subject have been published by Weaver and Bruce (2007) and Bruce (2012). The annual short course on grouting at the Colorado School of Mines in Golden, CO, broadcasts these developments, while numerous presentations at the USACE Infrastructure Conferences consistently tell the same story. It would be difficult to believe that any engineer
involved in a drilling and grouting project, whether as a contractor, owner or consultant, has not learned of, or has easy access to, the details of the great leap.

2.6 Codification

Various agencies, at different times, have produced “Grouting Manuals,” principally because a construction process, such as drilling and grouting, does not lend itself to the production of a Standard. The Manual of the Water Resources Commission of New South Wales (1980) is a classic example, and formed the basis of Houlsby’s hugely influential textbook of 1990. In the U.S., the Corps of Engineers “Grouting Technology Engineers Manual” (EM1110-2-3506) of 1984 constitutes a comprehensive summary of the technology as traditionally implemented. The USACE’s Manual was totally rewritten under contract to Gannett Fleming, Inc. in 2009, and was then subject to intense review by the Risk Management Center prior to its issuance on July 31, 2014. This document fully describes the elements of the “great leap,” and will doubtless represent the recognized standard of care for decades to come in North American practice.
3. CUTOFF WALLS FOR DAMS

3.1 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 11). 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.

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 12), 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 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 various phases of grouting are provided by Bruce et al., 2014.
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 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 Arturo Ressi de Cervia. Their approach was to build a continuous concrete 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 concerns, 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 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 installed safely through an existing, operational dam. Unprecedented levels of quality control, assurance and verification were developed and enforced (ENR, 1976; Dunn, 1977; 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 reemerged and, following intensive investigation and instrumentation, the USACE declared in January, 2007, the dam to have a Dam Safety Action Classification I status, i.e., a scenario demanding immediate intervention. They therefore reduced the lake elevation to 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 wall. (This is an excellent illustration of the “Composite Wall” Concept referred to in Section 2 above, and also used on several other major USACE and TVA embankments on karst (e.g., Mississennewa Dam, IN, Clearwater Dam, MO, Bear Creek Dam, AL and Center Hill Dam, TN.) The new 24-inch-thick wall which was to be built upstream and independent of the first, was to extend 1,650 feet beyond and 75 feet below the existing wall to provide 980,000 square feet of cutoff (Figure 5) at a maximum deviation off vertical of 0.25%. Strict tolerances governed strength, permeability and continuity, and practical restraints, driven by dam safety concerns, were placed on operational aspects such as the minimum allowable distance between open panels. The area near the concrete structure was designated the Critical Area, given its karstified geology, construction details and previous seepage performance characteristics. Given the critical status of the dam, speed 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 acceptance criteria. Most importantly, the safety of the dam had to be assured during all activities, including penetration of the embankment, crossing 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.

### 3.2 Availability of the Technology

The original 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) and conventional clamshell excavation (to remove the ground between the guide pipes) using biconvex clamshells (Figure 6). 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 N. American staff, many of whom had the diaphragm walls at the World Trade Center site in the late 1960’s on their long resumés.

Around the time of the 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 7 and Photograph 13, a hydrofraise comprises a rigid steel frame upon which are mounted cutting wheels and a powerful reverse circulation pump. The hydromill is introduced into a 3-6 m deep “starter trench,” already filled with bentonite slurry, and the cutting wheels and suction pump are activated. Cut debris are
removed from the trench in the bentonite slurry by the suction pump. The slurry is “cleaned” at
the surface desanding plants and clean slurry is fed back into the trench, supplemented by fresh
slurry, to ensure the trench remains topped up. Subsequent technical developments include
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). Standard widths range from 0.6 to 1.5 m, but
special machines have been produced to provide up to 2.2 m widths. Rock of up to 20,000 psi
unconfined compressive strength can be cut.

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 Joussellin, 2015). From 1973 to 1974, about 1,975 m² 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 mill for a dam cutoff was at Jebba Dam,
Nigeria, where in 1981 and 1982 over 36,400 m² of plastic concrete wall were installed to depths
of over 65 m (Soletanche, 2002). This was followed by similar 65 cm thick plastic concrete
cutoffs at Brombach Dam, Germany in 1983-1984, and again in 1985. These cutoffs totalled
over 55,000 m² and had a reported maximum verticality deviation of only 0.13% (Soletanche,
1999). However, the first remedial dam cutoff installed with a mill was at the USACE’s St.
Stephens Dam, SC in 1984, featuring 7,800 m² of plastic concrete wall, 65 cm thick, plus 2,800
m² of soil bentonite panels. This was soon followed by the test section at Reclamation’s
Fontenelle Dam, WY in 1985, and the subsequent production work of 1987-1988, together
totaling 85,000 m² of cutoff (Bruce et al., 2006). By the same period, three trial panels had been
successfully installed to 100 m depth, near Milan, Italy, with deviations controlled to 0.1 to 0.6% (Bruce et al., 1989).

Thereafter, hydrofraises were used to wholly or largely construct similar remedial walls in 8 other U.S. dams up to 2007 (Figure 8) for a total of about 240,000 square meters of cutoffs. Since then, further major remedial cutoffs have been constructed at several other U.S. dams, while the technique as deployed by Bauer Construction was recently used to build a cutoff wall over 120 m deep at the new Peribonka Dam, Quebec, totalling ___ square feet (Reference – Check DFI Magazine).

By the time, therefore, of bidding the second Wolf Creek project in 2008, the original leaps – comprising the “ICOS” method and the hydrofraise technique – had become common knowledge in the cutoff wall industry. The problem, however, remained that the risks – technical, quality, dam safety, and schedule – posed by the project were unprecedented. There was also the little issue of financial risk on a project estimated initially at over 340 million dollars. The solution adopted by the successful bidder – 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 Casalmaiocco, Italy, and an active participant in the landmark cutoff wall constructed at W.F. George Dam, AL from 2001-2003 (Ressi, 2003 and 2005; Siepi, pers com, 2011). TreviICOS’ particular group strengths were therefore in large diameter reverse
circulation drilling using Wirth pile top equipment from Germany (Photograph 14) and conventional clamshell excavation, while more recent corporate developments had advanced skills in directional drilling techniques (Photograph 15), as well as with hydrofraise technology.

As example, Chiarabelli and Pagliacci (2013?) reported on a 250 m 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 (Photograph 16).

Equally, Soletanche were by 2008 long established as a leading specialty geotechnical contractor in N. America and had acquired Nicholson Construction Company in addition to other construction assets. The company had continued to develop hydrofraise technology, with a focus on improving productivity and verticality control methodologies (Guilland and Hamelin, 19__). In particular, a new generation of hydrofraise had recently been developed (Photograph 17) capable of efficiently and precisely excavating the 72-inch wide, 535,000 sft “Protective Embankment Concrete Wall” conceived as protection to the dam embankment and its contact, during the subsequent drilling in the underlying rock to create the secant pile cutoff (Figure 9).

This “disposable” wall would 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 WDTH) were used as pilots for the large diameter piles. Eighty percent of these pilot holes subsequently had deviations at 282 feet depth of less than 3 inches (Santillan and Bedford, 2012).

Combining these 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 late 2008. Integral support was provided 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 ACT with Gannett Fleming. Extremely sensitive deviation monitoring instrumentation was specially designed and tailored for the major pieces of drilling and excavation equipment.

3.3 Owner Risk Acceptance

Faced with an extremely delicate dam safety situation, the USACE and its Board of Consultants in 1975 made an extraordinarily courageous decision to adopt the 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 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 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 Demonstration Sections in areas of lowest criticality first, before work was permitted along the rest of the project.

### 3.4 The Success of the Project

The second Wolf Creek wall employed nine different specialty construction techniques to eventually assure that the specifications in terms of verticality, strength, permeability and thickness were met, and that the work was conducted in ways preserving the safety of the dam (Santillan and Bedford, 2012). 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 __). 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 350 quality control tasks were conducted each day. The wall was completed 9.5 months ahead of the revised target date. The 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 fully restored.

### 3.5 Technical Publications
In addition to numerous informational and promotional publications by the USACE and the contractor, there have been at least 12 technical publications between 2010 and May, 2014. 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 international conferences in Venice, Seattle and Stockholm, in association with ICOLD and DFI. Doubtless there will be further publications dealing with the short- and medium-term performance of the cutoff as more data and observations are compiled by the USACE.

### 3.6 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 existing Engineering Manual EM 1110-2-1901. The draft is currently being reviewed internally by the USACE, and externally by representatives of the DFI, and the final version will be released publically in September, 2015 (Paul, Halpin, Pers Coms, 2015). 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 scheduled to appear in 2016. In addition, the Bureau of Reclamation is finalizing a new Design Standard on cutoff walls, under the guidance of Mark Bliss. This document is also scheduled to appear in August, 2015. These documents will provide strong support for the existing ICOLD Bulletin #150, and the European Standard EN1538.
As a final point, it may be observed that many of the technical “lessons learned” during the more recent works at Wolf Creek Dam, 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 indicates a strong trend away from Performance-type specifications towards more Prescriptive specifications. This has come as a result of sharing the experiences of Wolf Creek Dam with industry at large. 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 will not slip in the face of commercial pressures, on future projects.
4. DEEP MIXING

4.1 The Exceptional Nature of the Project

It is widely accepted that the Deep Mixing Methods were first developed, independently, in Japan and Sweden in 1967 (FHWA, 2000). The Japanese technology (mainly using fluid grouts to blend with the soil) was introduced into the U.S. through SMW Seiko Inc. in 1986 and the Swedish methodology, featuring only dry “binder” injection, was introduced in 1996 by the Stabilator Company. Other U.S.-based contractors (e.g., Geo-Con, Hayward Baker, Recon, Schnabel and Malcolm) developed their own variants while other Japanese (e.g., Raito) or European owned contractors (e.g., TreviICOS) also began to introduce their own approaches.

Throughout the period to 2008, landmark case histories were conducted for dam remediation (Bruce, 2012), highway construction (FHWA, 2000) and environmental remediation (Reference) in permeable, liquefiable, compressible and/or contaminated soils throughout the country. All these projects, regardless of the contractor or the methodology, shared commonalities, the most important of which were:

- All applications featured vertical axis mixing (with one or multiple shafts) and so with limited capability to vertically blend of soil with the binder to produce homogeneous “soilcrete” product. In other words, the vertical variability in the soilcrete reflected closely the vertical variation in soil type. A classification of the various vertical axis DM Methods as of 2000 was produced by FHWA (Figure).
Grout pressures were low, and no attention was paid to the significance of Blade Rotation Number (BRN) as a real time control over assuring homogeneity.

Real time operational parameter control recording was based largely on manually read instruments (e.g., pressure gauges, flow meters) or fairly basic electronic recording, monitoring and display systems originally developed in the 1980’s.

There was common reliance on wet grab sampling, or surface spoil sampling to generate screened samples for strength testing, as opposed to the use of coring and subsequent in-hole testing.

Consequently, test data recorded within and between projects were highly variable, particularly with respect to soilcrete strength and the homogeneity in plastic and organic soils. Such heterogeneity routinely proved the basis for contractual dispute since the respective technical and commercial expectations of the parties were not satisfied. It may also be observed that the bidding atmosphere was extremely competitive, with a common scenario on each project being most of the pack being within, say 10% of each other’s price, but one contractor – not always the same one! – being significantly lower. Opportunities for contractors to offer performance-based solutions using Deep Mixing were rare, since owners had little experience upon which to make informed selection decisions. Efforts by professional bodies (such as the Geo-Institute), trade associations (mainly the Deep Foundations Institute) via a series of short courses and even the FHWA through its support for State of Practice Reviews (2000a, 2000b, 2001) and state-funded,
combined research (M.E.) were unsuccessful in raising technology standards, inspiring innovation or increasing user acceptance.

Hurricanes Katrina and Rita, which devastated the Gulf Coast in August and September, 2005, respectively, were in different ways the progenitors of the “great leap” in Deep Mixing in the U.S. The gestation period was 3 years, and twins were born.

An archetypical research and development project had been completed by the New Orleans District of the USACE in 2001 (References). Under the leadership of Peter Cali, this initiative had again proved the technical viability of DMM in the deltaic soils (Bruce et al., 2012) previously demonstrated in the late 1990’s by Hayward Baker at Pascagoula, MS. While the technical advantages and potential benefits of DMM had been proved by the research, the commercial and strategic cases for its use in the deltaic debris of the Mississippi Valley had not been sustained – in 2001 – and the outcome was not viewed by the Government as having attractive, immediate (or ever) cost benefit potential.

Immense demands on time and resources were placed on the engineering community by the USACE’s Task Force Guardian which was stood up in late 2005. Guardian’s mission, in simple terms, was to ensure the safety of New Orleans and vicinity during the imminent hurricane season of 2006 (held to begin on the first of June of that year). Many of the fast track flood prevention projects commissioned by the USACE involved the construction of new canal gate structures, and the raising of levees in certain critical areas such as in Plaquemines Parish. The treatment and improvement of the very soft, organic deltaic soils was an integral part of many of
these projects, and over the following few years, numerous DMM applications were undertaken (Table, Reference). The methods used were characteristic of the day, and had changed little in 20 years.

The Hurricane and Storm Damage Risk Reduction System (HSDRRS) was conceived by the USACE in the aftermath of Task Force Guardian to definitively protect New Orleans from storm surge. A 5.5-mile-long levee section of the Lake Pontchartrain and Vicinity (LPV) Hurricane Protection System in East New Orleans was designated as Contract LPV 111. This particular contract presented unprecedented challenges that required innovative approaches in design, contracting, and construction (Cali et al., 2012). The levee is adjacent to the Bayou Sauvage National Wildlife refuge operated by in the U.S Fish and Wildlife Service (USFWS) (Figure). The Bayou Sauvage Wildlife Refuge is the largest urban National Wildlife refuge in the United States. Two pump stations are located along the levee, Pump Station 15 near the center of the levee section along the GIWW operated by the New Orleans Sewage and Water Board, and a smaller pump station on the north-south leg of the levee operated by USFWS. The levee is divided into three hydraulic reaches, 11B (north-south leg), and 12A and 12B on the east and west sides of Pump Station 15, respectively. The subsurface conditions and design procedures for each of the three reaches were generally similar.

The levee was originally built to Elevation 9.0 feet NAVD88 (2004.65) then raised in three stages to EL 17 feet in the 1970’s. During Hurricane Katrina, it was overtopped and severely damaged, but was quickly repaired and raised to EL 18 feet. The new design required raising the
levee to the 100-year level of flood protection, which resulted in a further raise to EL 27.5 feet (Top of Protection Elevation) for a Still Water Elevation at EL 19.7 feet.

In concert with the more stringent design standards of the HSDRRS and for schedule, access and environmental reasons, Deep Mixing was required to improve the foundation for greater slope stability and to minimize consolidation settlement. To meet the June, 2011, completion deadline, 1.7 million cubic yards of mixed soil were to be created along with the placement of over 1.1 million cubic yards of fill. The mixed soil was designed to be in buttresses transverse to the levee axis, at 15.5-foot centers (Figure). The construction Notice to Proceed was issued to the successful contractor in September, 2009. Clearly the amount of work, the intensity of production (and its control over resources), and the difficult nature of the soils themselves, greatly elevated the status of this DM project, which was to become the largest ever undertaken in the U.S. and one of the largest ever outside Japan. Thus, a “great leap” was required of the Deep Mixing industry to satisfy the technical, productivity, quality and environmental demands of the project.

The second twin appeared in Florida at about the same time. Lake Okeechobee in southeastern Florida is surrounded by a very heterogeneous levee known at the Herbert Hoover Dike, on which early construction by local agricultural groups first began around 1915 utilizing mostly sand and topsoil (Garbin, Evans and Hussin, 2009). Portions of the original embankments were overtopped by hurricane-induced surges in 1926 and 1928, resulting in the loss of over 2,500 lives. As a result of Government intervention, about 84 miles of levee were reconstructed by the USACE between 1932 and 1938. A major hurricane in 1947 emphasized the need for additional
flood protection, and the current dike system for Lake Okeechobee was completed in steps by the late 1960’s. The dike system now consists of about 143 miles of levee with nineteen culverts, hurricane gates, and other water control structures. Lake Okeechobee has become the third largest freshwater lake in the continental United States, draining to the ocean through the Everglades. The levee crest is typically at around elevation +36 feet, and the lake is normally at elevation +10 to 13 feet. However, sections of the levee are prone to instability due to seepage and piping accelerating rapidly when lake levels increase beyond certain elevations in extreme rainfall events (Davis, Guy and Nettles, 2009). Studies conducted in the aftermath of the New Orleans disaster confirmed that sections of the levee justified the USACE’s DSAC-1 classification, so requiring “urgent and compelling” action. These sections, or “reaches” were to be addressed in a prioritized fashion (Figure) to mitigate piping concerns and to therefore ensure dike stability during periods of high lake level.

The conceptual remediation of the critical 22.4-mile-long Reach 1 was a partially penetrating cutoff wall, typically from 50 to 90 feet deep, extending through the extremely heterogeneous embankment and foundation soils which often contained significant thicknesses of peat (Figure). An early 2006 demonstration section conducted with the backhoe excavation methods as previously used with success in the Sacramento levee system, did not provide satisfactory results: alternative methods to create the cutoff had to be found.

4.2 Availability of the Technology
Initial estimates for the LPV 111 project indicated that 10 DMM rigs would be required to operate round the clock for 10 months. This was based on the use of traditional Deep Mixing techniques and productivities, and was an estimate severely at risk to poorer than anticipated productivity, and quality (which would necessitate rework). TreviICOS (TIS) were the successful bidder for the Deep Mixing, under the novel Early Contractor Involvement procurement method used by the USACE, described in Section 4.3, below. The parent group of TIS (Trevi Group) also owns Soilmec, a manufacturer of specialty ground engineering equipment. Thus, in-house resources could be quickly mobilized to provide the eight semiautomatic grout batch plants which were spaced at about 1,500-foot centers along the project, in a total of 12 locations. Each plant consisted of one high-speed mixer, one agitator, one high-pressure pump for each DMM shaft on each rig, two vertical cement silos, one horizontal cement “pig,” and a 20,000-gallon water tank (Photograph).

Eight DMM rigs were mobilized by TIS from many different corners of the world. Soilmec provided two single shaft rigs (SR70 and SR80) for working in more restricted areas (Photographs), and three larger double shaft rigs (SR-90). These rigs were configured to use the recently developed TREVI Turbo Mix (TTM) method, featuring grout injection at high pressures (and so very effective soil blending characteristics) to supplement the normal mechanical mixing provided by the rotating blades (Reference). This high energy combination had been developed by the Trevi Group specifically to enhance productivity and improve homogeneity especially in variable, difficult soils. Three other rigs were provided by FUDO Tetra Corporation, and these operated the CI-CMC systems of injection and mixing. The prime “leap” of CI-CMC was the technique of injecting compressed air with the slurry immediately before it exits the injection
vents on the cutting blades. The air-slurry “emulsion” was found to very efficiently cut the soil, thereby reducing the torque requirements on the mixing shaft and improving productivity.

The 5.25-foot diameter mixing shafts were arranged at 4.25-foot centers for the double axis rigs. The design flexibility afforded by the ECI contract allowed the overall number of columns to be reduced while still providing the 30% volume replacement ratio required by the specification. Diameters are typically 3 feet for conventional DMM systems.

In order to most efficiently and accurately set up the rigs, and thereafter monitor, control and record the mixing parameters, advanced computer-based systems were developed to relay data in real time to both site and head office management locations. The central DMS system allowed mixing parameters to be preset in up to 4 different soil types in any single element. Continuous analysis and interpretation of the data led to optimization of construction parameters, specifically as related to production time and materials consumption (Figure) (Bartero et al.)

Finally, the specifications called for the quality of the mixed soil to be assured by the coring of 3% of the elements, to full depth. To keep up with the DM production, three coring rigs were required to operate six days per week. Given the minimum target unconfined compressive strength was 100 psi at 28 days, special attention had to be exercised in this operation, requiring very careful selection of coring techniques and equipment, and intense training of the drillers.

For the Herbert Hoover Dike remediation, the USACE solicited technical proposals from specialty contractors based on a Performance Specification. The specification detailed the
length, depth, location and minimum thickness of the wall, its acceptable strength range, maximum in-situ permeability, continuity and degree of homogeneity. The overall project was broken down into discrete, continuous “reaches,” each thousands of feet in length. From the total of eight schemes submitted, the USACE selected three to be used as the exclusive basis of each of the three successful bidder’s subsequent competitive commercial offers.

One of the three techniques selected for competitive bid was the Trench Remixing Deep (TRD) Method as offered by Hayward Baker, Inc. The TRD system was originally conceived and trialed in Japan in 1993. It was not used and very little known in the U.S. until its import under license in 2005. Simply, it is akin to a giant vertical chainsaw (“post”) which is pulled through the ground creating in its wake a continuous soilcrete wall by blending the cuttings with grout injected through ports in the toe of the post (Figure and Photograph). It has been used to build walls up to 170 feet deep with widths of 18-34 inches and by the time of the Herbert Hoover project had been used successfully in over 300 projects in Japan.

One particular attraction of the TRD method for the Lake Okeechobee project was its ability to blend the soils vertically due to the vertical “ripping” and displacement action of the cutting chain during its advance. Given the heterogeneity of the soils on this project, this blending action was able to assure an unprecedented degree of soilcrete homogeneity for a Deep Mixing technology.

### 4.3 Owner Risk Acceptance
In each case – LPV 111 and Herbert Hoover Dike – the owner was the USACE, and in each case the risk was managed and accepted in different ways. At LPV 111 the risks were as much associated with schedule as they were with the quality of the product, and a unique contractor procurement vehicle was employed by the USACE to accelerate completion of the project. The USACE had gained extensive experience in the use of conventional deep mixing in New Orleans between 2001 and 2007. While not all the projects yielded perfect results, deep mixing was viewed as an acceptable ground improvement technique. Having determined that a deep mixing application of unique scale and intensity was indeed an integral part of the LPV 111 project, the USACE’s Hurricane Protection Office (HPO) convened an Industry Forum in August 2007 in New Orleans to brief potential contractors, binder suppliers, earthwork contractors, designers and local sponsors. This was intended to explain the scope and schedule and to solicit input from industry: basically industry was put on notice. The contract for LPV 111 was awarded on June 29, 2009 to the Joint Venture of Archer Western Contractors, Ltd. and Alberici (AWA), in alliance with TreviICOS South (TIS). The contract included preconstruction services under the arrangement known as Early Contractor Involvement (ECI). The contract was awarded with the design at 35%, and although the USACE and the Designer of Record (URS Corporation) were responsible for the final design, input from the contractor’s team was required during the four months of project mobilization.

Specific items researched and ultimately incorporated in the specifications and work program for the Deep Mixing included:

- Evaluation of desk studies of previous works in the area.
- Mix designs for the bench scale tests (in 4 phases)
- Binder contents and compositions.
- Reliability of the binder component supply chain.
- DM element layout and diameter.
- Equipment requirements.
- Scheduling and sequencing.
- Costs associated with all options.
- Quality Control procedures.
- Quality Assurance requirements.
- Frequency of testing and standards to be utilized.

When the project had reached about 75% design, and further site investigations and the bench tests had been conducted, the first of the five full-scale Validation Tests was carried out. These tests permitted construction parameters to be optimized for each section of the project, and was followed by the full production works in each section.

At Herbert Hoover Dike, the USACE realized in the initial demonstration area that traditional construction methods would not be effective: alternative techniques would be required, as would alternative methods to procure them. The USACE therefore implemented a process wherein contractors were invited to offer their own particular method for building the cutoff and, as noted above, three of eight contractors were selected to thereafter bid competitively on each contract. The technical requirements for each contract were common, and had each to be satisfied. The wall was required:

- To be continuous and homogeneous.
- To be a maximum 36 inches and a minimum of 18 inches wide for the entire depth including at overlaps between panels.
- To have an in-place permeability of less than $1 \times 10^{-6}$ cm/s.
- To have a minimum unconfined compressive strength of 100 psi and a maximum of 500 psi as measured in core samples.
- To be vertical.
- To be chemically compatible with the groundwater and soil conditions.
All these performance parameters had to be proved via a quality control and assurance program featuring:

- daily bulk sampling and deep-grab sampling from the mixed panels at designated depths;
- core drilling every 200 feet along the wall alignment, including:
  - color photos and high-resolution Optical Televiewing of the entire depth of each cored hole;
  - a recovery of at least 95 percent;
  - inclinometer readings to verify verticality;
  - falling head *in-situ* permeability testing;
  - an assessment of the homogeneity of the wall.

Five-hundred-foot-long demonstration sections had to be first conducted in each contract to demonstrate to the Government’s satisfaction that the contractor’s means, methods, and materials were capable of satisfying the project goals in that area.

It may be observed that the risks to schedule and quality in each of these projects were immense. However, in each project, the owner mitigated the risks he had assumed in accepting new technologies, by adopting innovative contractor procurement practices, and establishing a Performance-based approach to the Specifications. Further, these Specifications defined very clear, realistic and verifiable elements of quality control and assurance. Prime amongst these was the requirement for the Contractors to fully demonstrate the capabilities and acceptability of their methods in extensive field test programs prior to being permitted to commence the production works.

### 4.4 Success of the Project

In every aspect, the Deep Mixing conducted at LPV 111 was an outstanding success. The work was completed within 14 months, by working 24 hours per day, 5.5 days per week. During this period, 18,022 individual elements were installed, using over 460,000 tons of slag cement binder,
which often required as many as 120 truck deliveries per day to site. Regarding quality
assurance, over 500 holes were cored yielding an average recovery of 99% as compared to the
80% acceptance criterion, and showing no inclusions greater than 12 inches in size. 5,082
individual core strengths were tested, yielding an average 28-day UCS of 292 psi (median 275
psi, standard deviation 126 psi) compared to the 100 psi criterion. No environmental problems
were recorded. As an added bonus, most of the 500,000 cubic yards of spoils (recycled
embankment material) were incorporated into the levee reconstruction, rather than be removed
from site for remote disposal (Druss et al., 2012).

The successful completion of the cutoff walls installed at Reach 1 at Herbert Hoover Dike
between 2008 and 2012 represent a significant achievement, shared between each of the three
contractors and their respective methods: Hayward Baker (TRD), Bauer Construction (CSM)
and TreviICOS (cement bentonite cutoff using grabs and hydromill). Each of these contractors
(and techniques) had their “moments” as could reasonably be expected given the scope,
complexity, urgency and high acceptance standards of the project. Each contractor learned
fundamental lessons which subsequently enhanced all efficiency, reliability and quality of the
product they now provide. Regarding TRD, it’s “moment” was associated with an apparent
dichotomy between the retrieval of perfect cores, but subsequent evidence of cracking in the in-
situ borehole walls themselves, as revealed by the Optical Television inspection. Modifications
to coring techniques, and measures to limit the thermal stresses which naturally develop in long,
continuous, cementitious structures, eliminated the problem and allowed all sections to be
completed in full satisfaction of the Specification requirements.
Overall, the TRD method was used to successfully construct over 20,000 lineal feet of cutoff wall. An outstanding degree of uniformity was recorded in the properties of the wall (e.g., Figures x and y), while the Geologger inspection of the cored Verification Holes further confirmed the high degree of in-situ homogeneity (Photograph x).

### 4.5 Technical Publications

One complete session of the 2012 Geo-Institute Conference on Grouting and Deep Mixing was devoted to the various aspects of LPV 111 and involved 6 papers. Other papers have also been published at the Seventh International Conference on Case Histories in Geotechnical Engineering (Schmutzler et al., 2013), at an International Symposium in Brussels (Leoni and Bartero, 2012) and in the ISSMGE Bulletin (Schmutzler et al., 2011). These are in addition to papers in trade magazines (e.g., Schmutzler and Leoni, 2013) and presentations at many regional seminars.

The achievements at Herbert Hoover Dike have also been widely disseminated such as in the ASDSO Conference (Garbin, et al., 2009) and in the textbook “Specialty Construction Techniques for Dam and Levee Remediation” (2012), in addition to numerous presentations at regional professional and trade short courses and seminars.

### 4.6 Codification
The lessons learned from employing these techniques have been incorporated into the USACE, Bureau of Reclamation, and DFI documents currently under preparation, identified in Section 3.6, above. Both companies have used these techniques on other projects, albeit of lesser scale. Competitors, old and new, have incorporated the information to improve their own internal processes, or to more aggressively promote similar techniques (as is the case with the One Pass Trench Method currently being used to construct a 70-foot deep cutoff at Whitehouse Dam, TX). There is also no doubt that the contents of the new FHWA Deep Mixing Manual (2013) have been heavily influenced by the experiences and lessons of LPV 111.

5. MICROPILES

5.1 The Exceptional Nature of the Project

Micropiles are small diameter (typically less than 300 mm) drilled and grouted elements used for structural support and slope and excavation support. They are installed by the type of equipment used in grout curtain, soil nails and ground anchor construction. Micropiles – compared to other types of deep foundation elements – are somewhat costly per lineal measure, but can be very cost effective in terms of load accepted per element, and in terms of deflection permitted per element.

Dr. Fernando Lizzi of Naples is the father of the micropile concept. He returned to his beloved homeland, having been an enforced guest of the British Empire from 1942-1946 in what is now Pakistan, together with thousands of his countrymen with whom he fought during the Libyan
Campaign, he saw a devastated Italy: historical structures and more recent infrastructures threatened and damaged in equal measure.

His guiding concept for remediation was both logical and binding – “primum, non nocere” (first, do no harm). By 1952, he had guided his company, Fondedile, S.A., into patented micropile design and construction methods which were as gentle and sensitive as the man himself:

- Supporting structures with a network of small diameter (< 100 mm) fully bonded, low capacity piles, crisscrossing in the ground like the root system of a tree (“pali reficulosi”).

- These networks acting in concert with the soil to create a simpatico soil-pile composite structure thus providing stability to already borderline unstable structures without creating major stress and strain changes within the structure being stabilized.

- Using very delicate drilling and grouting techniques so as to not disturb the existing foundations of the structure, or the soils below it.

The combination of Dr. Lizzi’s personality, energy, integrity and technology led to a remarkable growth in the fortunes of his company, and produced applications of micropiles throughout Europe, and at least three other continents. Fondedile established a presence in the U.S. in 1970 (Bares, 2007), and the first uses of micropiles for structural underpinning were recorded in the U.S. and Canada, in 1972 and 1973, respectively. His 1982 book “Static Restoration of Monuments” is the high water mark of his original work.
Thereafter, patents expired, competitive techniques emerged, economic cycles pressed, and certain business ventures failed – including several attempts in the then largely non-receptive environment of the U.S. Even the elegant micropile demonstration project sponsored by the FHWA for slope stabilization in Mendicino County, CA, in 1977 failed to convince the market of the cost-effectiveness of the micropile technique. At this low point in micropile history in the U.S. in the mid-1980’s major market opportunities opened for deep foundations within aging industrial and transportation facilities in the eastern and southern states, deep foundations for structures on karstic limestone, and slope stabilization for highways in the Appalachian Mountain chain.

Specialty contractors who already had the means, methods and mentality to install ground anchors and soil nails efficiently, naturally recognized that they had the design and construction capabilities to provide micropile solutions. The old houses of the East, Nicholson Construction Company, Schnabel Foundation Company and Goettle Construction led the way, Dr. Lizzi’s involvement long gone.

During the late 1980’s and the early 1990’s, the micropile market slowly advanced, restrained by owner’s distrust, cut-throat competitive pricing, and the glaring absence of a guiding referenceable standard of care. But, during that period, fundamental engineering discoveries were being made, and publicized, which would contribute to the understanding of why micropiles worked as well as they did (Reference). In this regard, the researches of John Kenney (Reference) and the full-scale testing organized in San Francisco by James Mason after the 1989
Lioma Prieta earthquake (Reference), and in Portland, WA (Reference) were fundamental, and the attention of large DOT’s (especially New York, California and Washington States) and the FHWA was engaged.

To further stoke the growing fire, personnel from the “mother companies,” and in particular Nicholson Construction Company, had moved to other career opportunities in the South and on the West Coast, naturally taking their knowledge and networks with them. Therefore, by the mid-1990’s, there was a vibrant knowledge base and a growing market demand across the country, amid an atmosphere of intense commercial competitiveness such as is typical of brothers in a dysfunctional family. Unfortunately but understandably, potential users of the technique, both in the public and private sectors, were confused by the various and respective claims of the specialty contractors (the consultants having been left far behind in this race): so what is the difference (or similarity) between a micropile, a pinpile, a root pile, a minipile?

Al DiMillio, the Geotechnical Research Manager of the FHWA, had tracked the rise of micropile technology and the benefits it could bring to U.S. practice, especially in the light of the needs from West Coast retrofits and East Coast urbanization. He commissioned a “State of Practice,” published in 1997 (Reference) which summarized and consolidated micropile knowledge in the U.S. One apparently minor, but deeply influential conclusion, was to adopt the generic term “micropile,” and to thereby set the contractors on the same terminological playing field.

Assisting as international advisors in this endeavor were specialists from Europe, foremost amongst whom, and by personal request of the Report authors, was Dr. Lizzi. This involvement
for him was, in his own word, “a wonderful surprise for an old man,” and a source of great personal satisfaction to him and his family until his death at the age of 89 in 2003.

The four volumes of the State of Practice was thorough but hardly inspiring reading for practitioners, and soon the FHWA commissioned an “Implementation Manual” (2000) encapsulating the more attractive and immediately relevant aspects of the 1997 opus, and constituting a comprehensive guide to micropile design, construction and testing.

Stepping back a little, it is clear that the leap itself was not the publication of the State of Practice Report in 1997, nor even the publication of the Implementation Manual in 2000. Rather, it was the product of the numerous working group meetings held – in 1994 and 1995 – with the international advisory panel and carefully selected engineers from ownership, consultancy, academia and construction throughout the U.S. The bases of rigorous design methodologies were developed, the choice of construction techniques and equipment was rationalized, and approaches to quality and control and assurance were sharpened.

Recognition of this new order in micropile technology came from two major international sources. The Hanshin Earthquake of 1995 set Japanese foundation engineers to seek new and immediate solutions for highway retrofit and reconstruction projects, while a serendipitous combination of market opportunity (timber piles rotting due to falling Baltic Sea Levels), a glut of high quality steel, and strong academic leadership (Prof. Jouko Lehtonen) provided Finnish engineers with a deep thirst for micropile knowledge.
The FHWA therefore sponsored the first International Workshop on Micropiles in 1997, primarily designed to transfer, in a practical manner, the findings of the U.S. researches, to a wider international audience. These workshops have been held at regular intervals internationally since, under the banner of the International Society for Micropiles (ISM) strongly sustained by trade organizations such as ADSC and DFI, as well as by corporate sponsorship (such as Bauer, Casagrande, Dywidag and Ischebeck).

5.2 Availability of Technology

The specialty geotechnical construction industry is, to parrot the NFL dictum, a “me too” business. This is hardly surprising given the open lines of personal communication between the engineers and operators in the various companies, most of whom have worked, or will work, for each other at some point during their professional travels. In this natural, informal way, similar or identical overburden drilling techniques come to be used (especially rotary, percussive and eccentric duplex) with minor regional variations; the grouting procedures and materials become identical; and the choices of reinforcement universal ("oil field secondary" casing, available in only a limited number of sizes) were common. Drilling rigs of practically identical mechanical capabilities were developed, principally by various Italian and German companies, who were fastest to react to the typical micropile challenges of providing high torque and pull out capacities in limited access and headroom environments. Any new drilling technique, e.g., the RotoLoc system of Center Rock Inc. (Reference), or new installation concept, e.g., the “self drilling” hollow bars of the late Ernst Ischebeck (Reference), immediately became the subject of
fraternal – usually nocturnal – discussions followed by universal adoption by the main competitor companies.

It is difficult to cite a business segment with such an open and symbiotic relationship between contractors, suppliers and manufacturers as the one that emerged in the renaissance period of micropiles in the mid-1990’s in the U.S.

5.3 Owner Risk Acceptance

The early days of micropile practice in North America did not reflect or engender a high or enthusiastic degree of owner acceptance: some potential users were concerned about the structural failability of piles with such high slenderness ratios, while other users were not – understandably – overwhelmed by the “trust me” approach adopted in the contractor-design approaches common in the early years. However, by the late 1980’s, sufficient design progress had been made by the engineering staffs of the major specialty contractors that a wide base of both private and State clients was confident in the technology. This growing acceptance was nurtured by the intense collaborative efforts of certain DOT’s, especially those controlling works in urban, karstic, seismic and mountainous terrains. The influence of the FHWA efforts enhanced these growing levels of confidence and risk acceptance, as did the support given directly and indirectly to potential owners and consultants by the trade associations and, of course, by ISM. By the time of the publication of the Implementation Manual in 2000, micropiles were seen as no more risky, and no less reliable than any other deep foundation technique, such had become their acceptance throughout the foundation industry.
5.4 Success of the Project

The “leap period” was punctuated by a series of high profile projects of unprecedented scale and complexity, including those at the United Grain Terminal, WA (Reference), Williamsburg Bridge, NY (Reference), and the Richmond San Rafael Bridge (CA) (Reference). These were conducted during years when micropiles were being routinely and widely installed for seismic retrofits and in karstic terrains (Reference), as well as in more traditional urban, industrial and slope stabilization applications (Reference).

It would be wrong to claim that every project progressed without difficulties: challenges can naturally be expected to be more common when constructing in difficult ground conditions and in difficult access environments, such as are intrinsic in most micropile applications. However, to the author’s personal knowledge, no micropile project has gone uncompleted due to reasons of constructability, and no micropile project has provided a built solution that has failed to meet the performance requirements of the project.

5.5 Technical Publications

Whereas the pre-leap days were characterized by a limited number of classic micropile papers (References), mainly by European specialists, the later years have seen an explosion of technical papers of domestic origin. The majority of these have been written – and continue to be written – by the contractors, always keen to capitalize on the fame of the new application, a large job, a
tweaked technique, or an analytical advance. An increasingly important contribution is being made by the Universities (Reference), and by a limited number of consultants (Reference). It remains accurate to say, however, that most of the micropile publications originate from, and are published by, trade associations. The ISM maintains a database of publications (Reference).

5.6 Codification

As noted above, the referenceable standard of care in N. America is the FHWA “Implementation Manual” (Reference) which describes the application, design, construction, testing and performance of micropiles. This document was most recently revised in 2005, and is used for both public and private sector work. In addition, the International Building Code (which relates mainly to private works) incorporated micropiles from 2006, while the AASHTO Standard (for Highway Construction) has featured micropiles from 2009.

The impact on market size is clearly illustrated in Figure 5.1, which plots the author’s best estimate of the U.S. market volume against the various years since micropiles were first employed in this country by Dr. Lizzi’s company. The rapid and sustained growth from the mid-1990’s onwards is a direct reflection of the original influence of the FHWA, and the continuing sustaining efforts of the trade associations and their members.

6. 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 four techniques used as examples above each satisfy all the criteria, but in subtly different ways relating to the initial demand and the industry response. For drilling and grouting, the leap comprised a group of incremental developments in the component processes, materials technology platforms and design concepts. A far reaching vision of an end product amalgamating all these elements was developed quickly by one contractor/consultant team in response to specific challenges posed by the technical and safety aspects of major dam remediation. For concrete cutoffs, 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 made on these earlier methods as a result of the challenges of the second Wolf Creek Dam remediation in 2008-2013. The Deep Mixing leap in 2008 comprised two parallel steps, one a newly-introduced methodology (TRD), the other a major enhancement of the traditional methodologies. Each emerged in response to the demands of a specific project of unprecedented scale and urgency, and each was facilitated by the innovative procurement vehicles adopted by the Federal Government. In contrast, the leap associated with micropiles was not technological nor yet relatable to one specific project. Rather, it sprung from a coalescence of industry perspectives from all market participants, precipitated by Federally-sponsored “State of Practice” studies and their resultant “Implementation Manual,” the referenceable standard of care for design, construction and testing.
Regarding the other four criteria, each is fully satisfied for all the four techniques under consideration: the proposed leaps were accepted by major Owners, the applications were successful, the details have been widely published, and the advances have been codified and are now well known by industry at large.

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 these four technologies (and others) are bound to happen one day and we must be ready and willing to embrace them – especially those of us of more senior years.

Karl Terzaghi served the Austro-Hungarian Empire as an engineering officer in Serbia during the First World War. On November 1, 1915, he wrote “War and technology, like fire, are stimulating in their primitive stages, but degenerate in their eventual achievements.” We would surely all like to think that, were he to somehow materialize on November 1, 2015, he would agree with us that technology in his beloved field has not experienced degeneration, but has continued to make “Great Leaps” as long as there are great challenges to be faced by our profession.

The Frontispiece of the seminal textbook “Foundation Engineering” by Peck, Hanson and Thorburn (1974) provides the iconic image of a mature, vaguely mysterious Prof. Terzaghi at work (Photograph X). The caption states:
“Karl Terzaghi (1883-1963)

Founder and guiding spirit of soil mechanics, outstanding engineering geologist, and preeminent foundation engineer. He was the first to make a comprehensive investigation of the engineering properties of soils: he created or adapted most of the theoretical concepts needed for understanding and predicting the behavior of masses of soil, and he devised the principal techniques for applying scientific methods to the design and construction of foundations and earth structures.”

This particular version of the image was not taken by me from the textbook: it was provided to me by my friend and colleague Rick Robertson of CH2M Hill International – Panama. Rick is the leader of the Locks Dispute Team, acting for the Owner of the Third Locks Project, ACP (Autoridad del Canal de Panama). I requested it during one of my frequent meetings with him and his staff, to whom I have acted as geotechnical advisor. Mr. Robertson sent it to me with the cover:

“Pinned up, watching over us in our day to day activities and reminding us of the observational method. Bringing a smile to my face.”

That, for me, Ladies and Gentlemen, is the true legacy of Karl Terzaghi:

- An educator, but more an inspiration.
- A scientist, but equally a communicator.
• A genius, but in reality the ultimate role model for all, despite – or because of! – his well-documented love of wine, women and song.