THE EVOLUTION OF SPECIALTY GEOTECHNICAL CONSTRUCTION TECHNIQUES: THE "GREAT LEAP" THEORY

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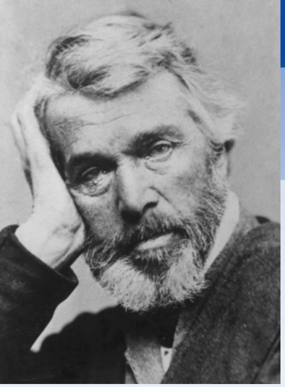
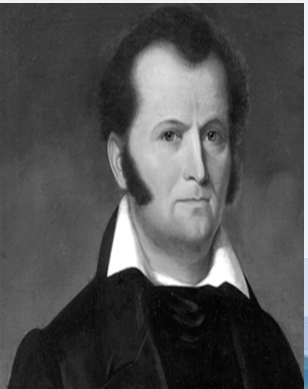
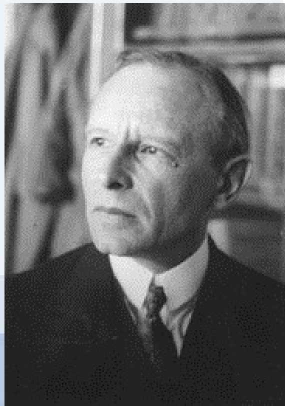
Terzaghi Lecture
September, 2015

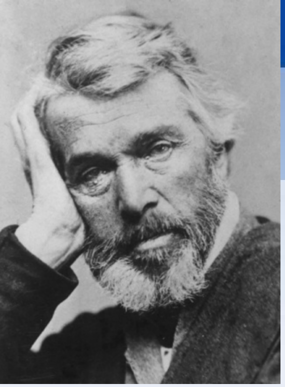


1. DEVELOPMENT OF THE BASIC THESIS

- Carlyle's "Great Man" Theory of History
- "Great Men" in Geotechnical Engineering Practice: The Terzaghi-Goodman-Peck Triangle, and Others
- "Great Leap" Theory Applies for Geotechnical Construction Techniques

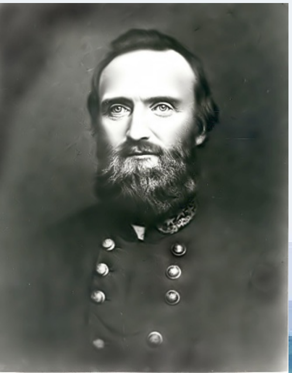


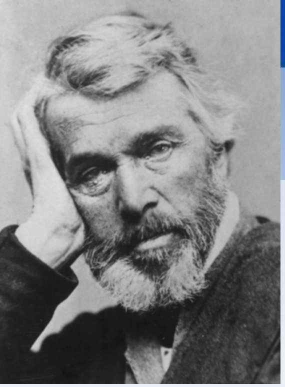




- “Great Leap” Theory demands the satisfaction of six successive criteria:

1. The project or group of projects must be of exceptional and/or unprecedented scope, complexity, and construction risk.
2. A Specialty Contractor with ingenuity, resolve, and resources, and an equipment manufacturer must both exist.
3. A responsible individual/agency for the Owner must be prepared to take the perceived risk of deploying a new technology or technique.
4. The project(s) must be successful!
5. Details must have been published widely in the scientific press.
6. Within a few years of completion, there must be some type of codification/standards document, permitting wider use by industry.

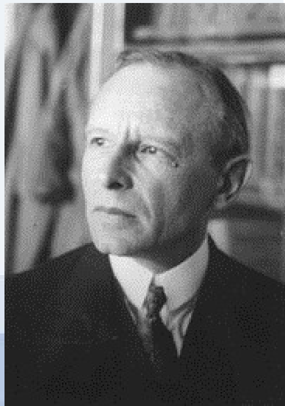




- The theory can be demonstrated by analyzing progress in 3 processes in particular:
  - Remedial grout curtains in rock
  - Cutoff walls for dams
  - Deep Mixing Methods

- Other processes could be used for illustration (e.g., rock anchors, micropiles, large diameter piling, soil treatment).

  - Time restraints mean only cutoff walls for dams will be considered in detail this morning.

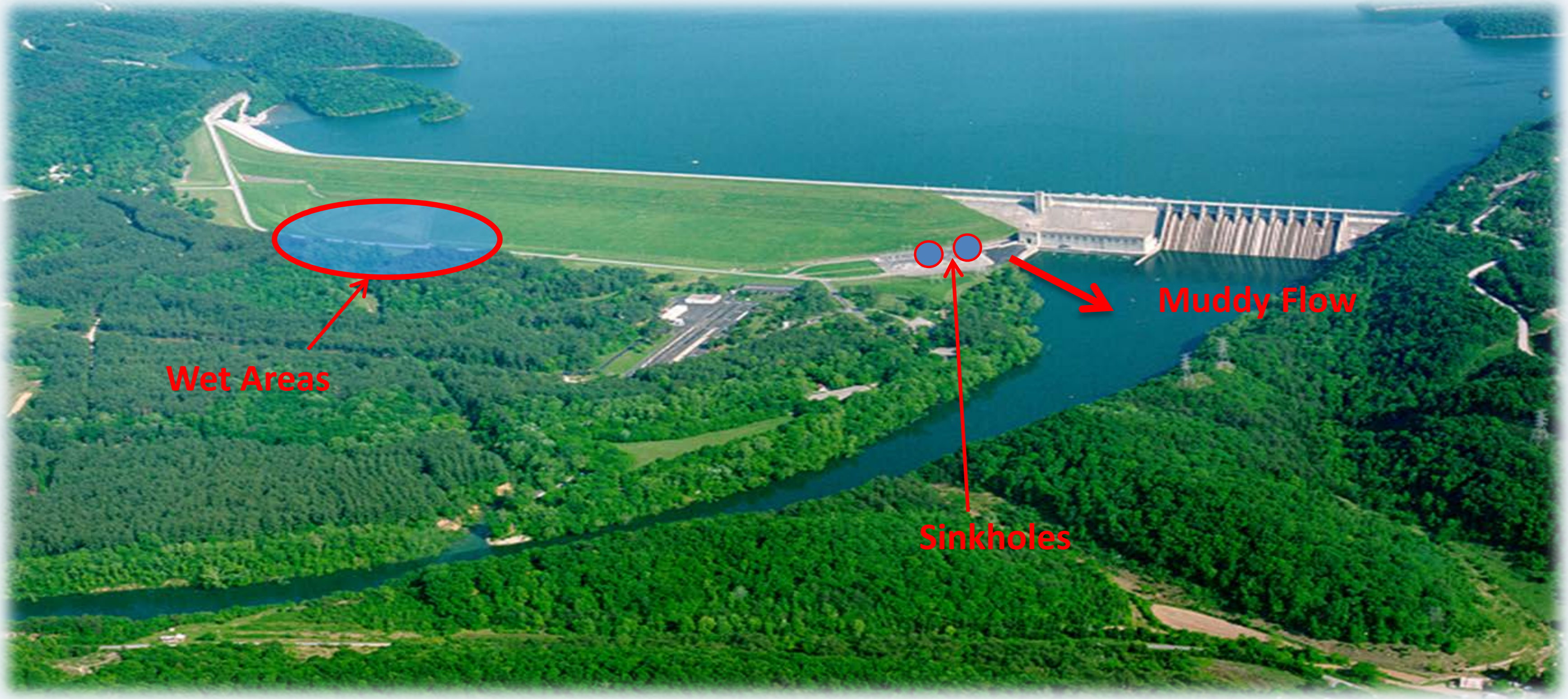


3. CUTOFF WALLS FOR DAMS

3.1 The Exceptional Nature of the Project

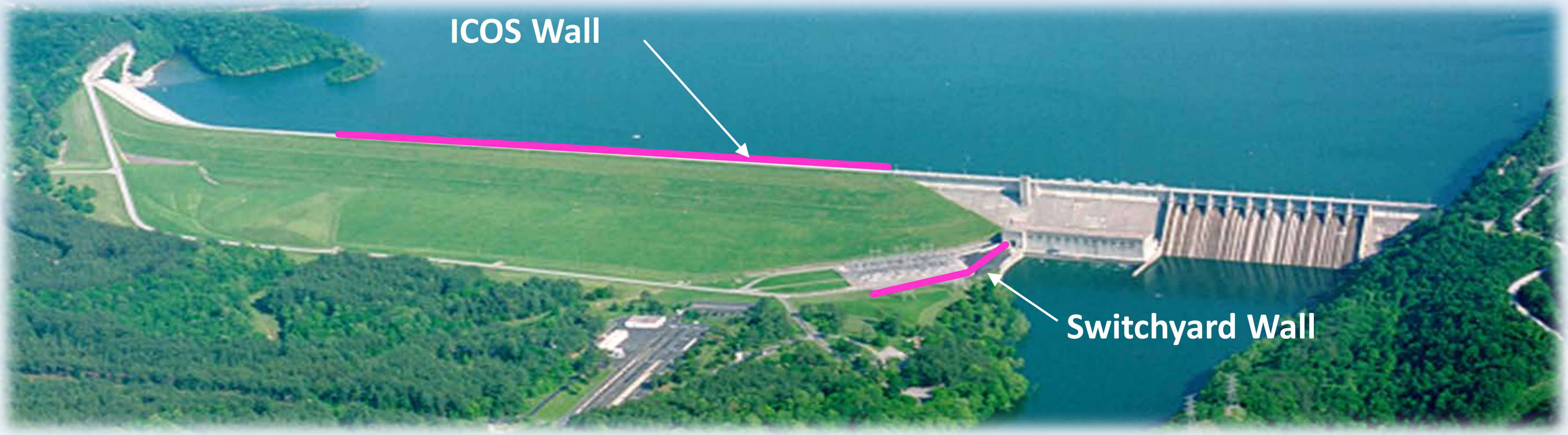
- Wolf Creek Dam, KY – a 3,940-foot-long homogeneous fill and contiguous 1,796-foot-long gated overflow section. Founded on Ordovician carbonates with major kastification. Retains Lake Cumberland and protects Tennessee.

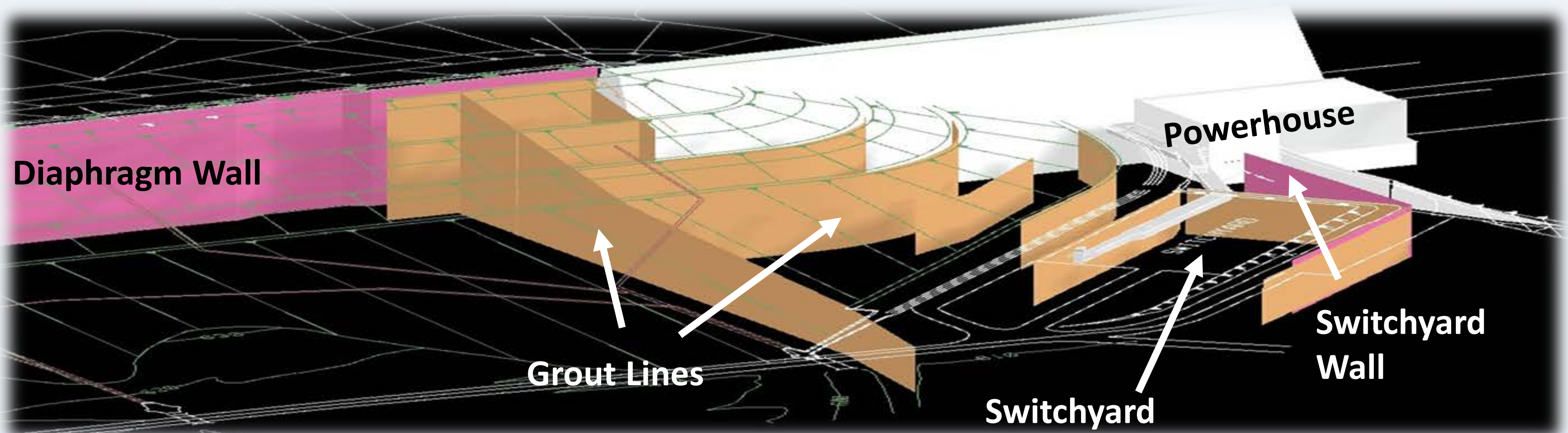
- Designed in the 1930’s, built from 1941-1943 and 1945-1952.
- Severe hydraulic distress observed after impoundment leading to emergency grouting by USACE in 1968-1970 and 1973-1975.



- Primary Failure Mode related to erosion and piping of natural soft karstic infill materials and clay backfill in the core trench.
- Need for “definitive solution” led to international competition, won by ICOS Corporation of America in 1975. This successful solution for an existing dam featured a concrete diaphragm wall built by a unique combination of rotary drilling and clamshell excavation, both by then well established techniques.

First Solution – Cutoff Wall and Extensive Grouting Campaigns





First Solution – Cutoff Wall and Extensive Grouting Campaigns

ICOS' barrier wall was installed along the centerline of the Embankment

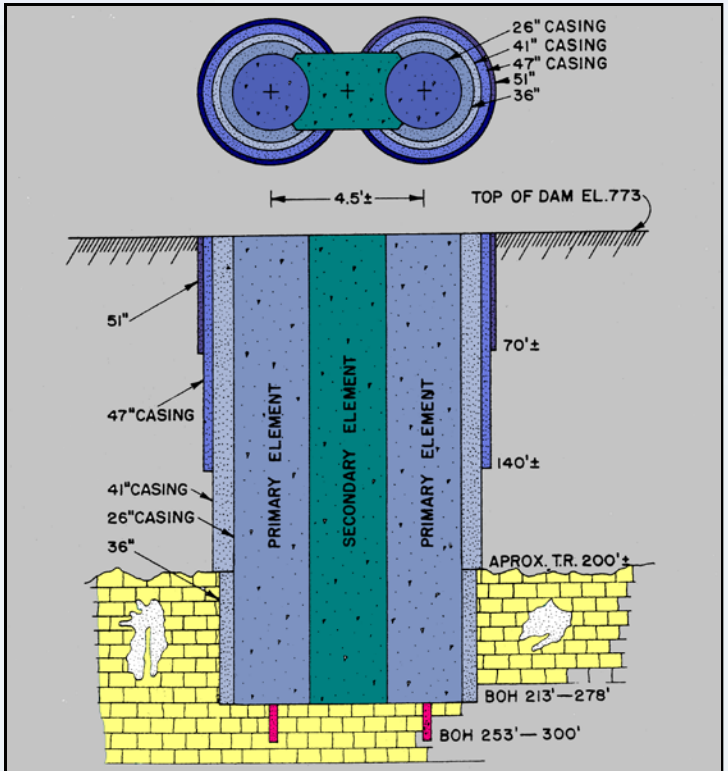
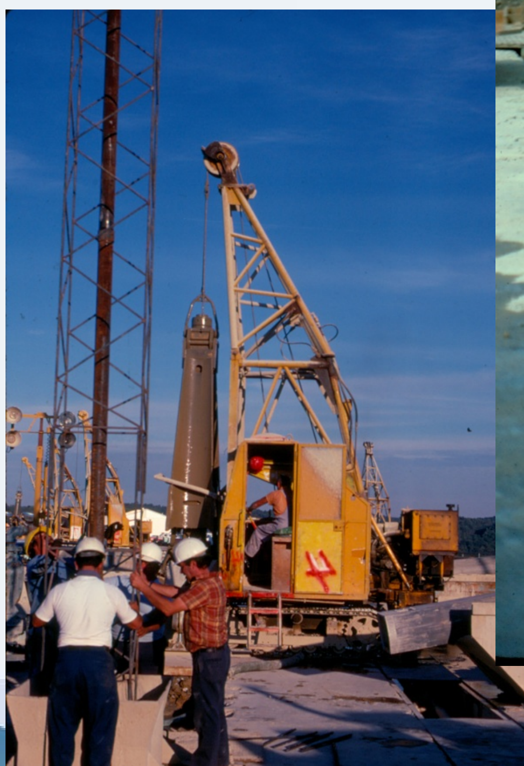


FIG.3 TYPICAL SECTION OF COMPLETED DIAPHRAGM WALL.

Approximately 990 Concrete to Steel Joints

- The main wall was 24 inches thick, 2,237 feet long, and a maximum of 280 feet deep. A secondary wall was built in the downstream switchyard.
- Built from 1975-1979 at a cost of 97 million dollars.



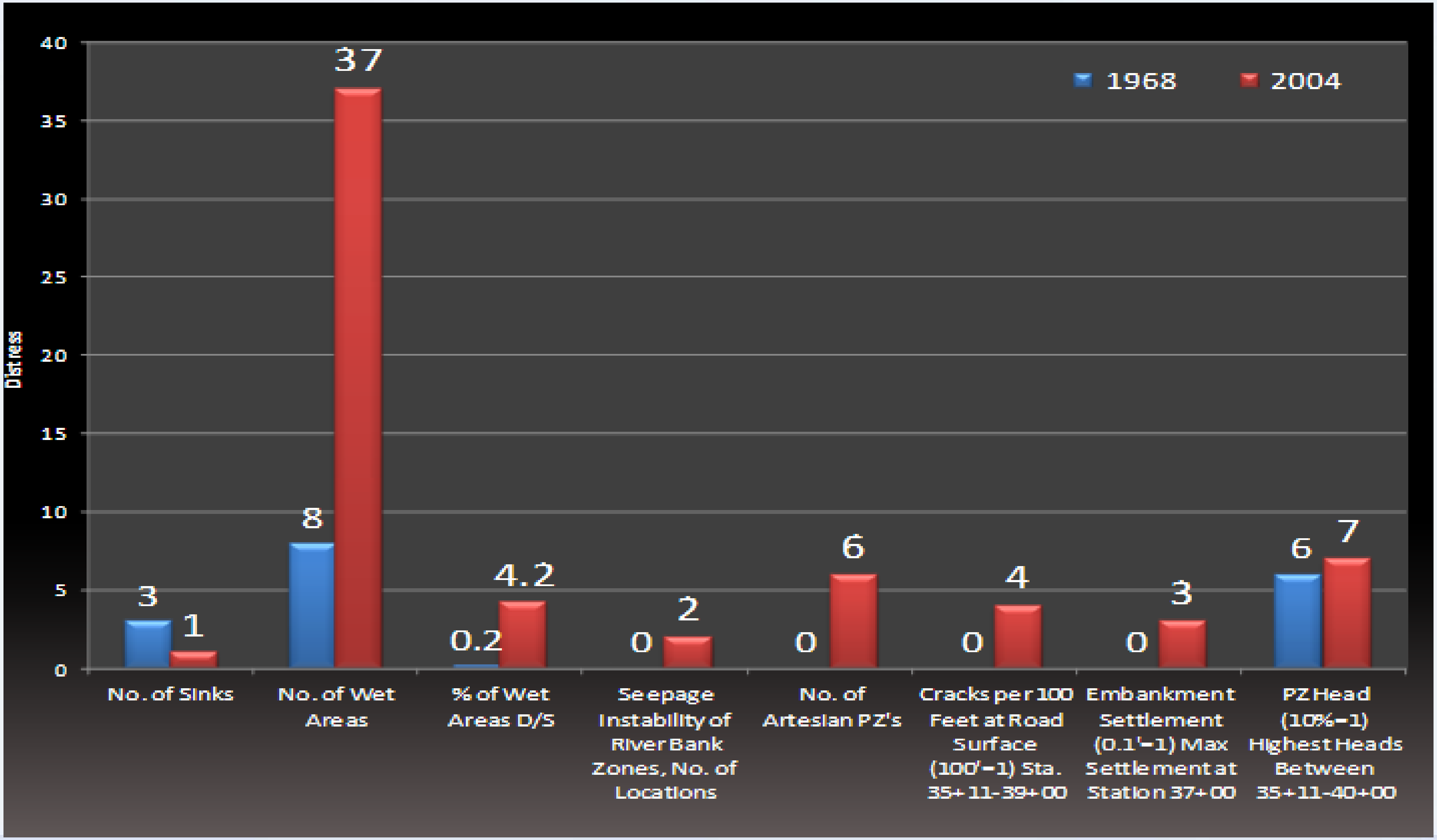
HOWEVER…

- During this original project, at least one member of the Board of Consultants (Dr. Peck) opined that the wall was neither deep enough nor long enough.

  …and of course he was correct.

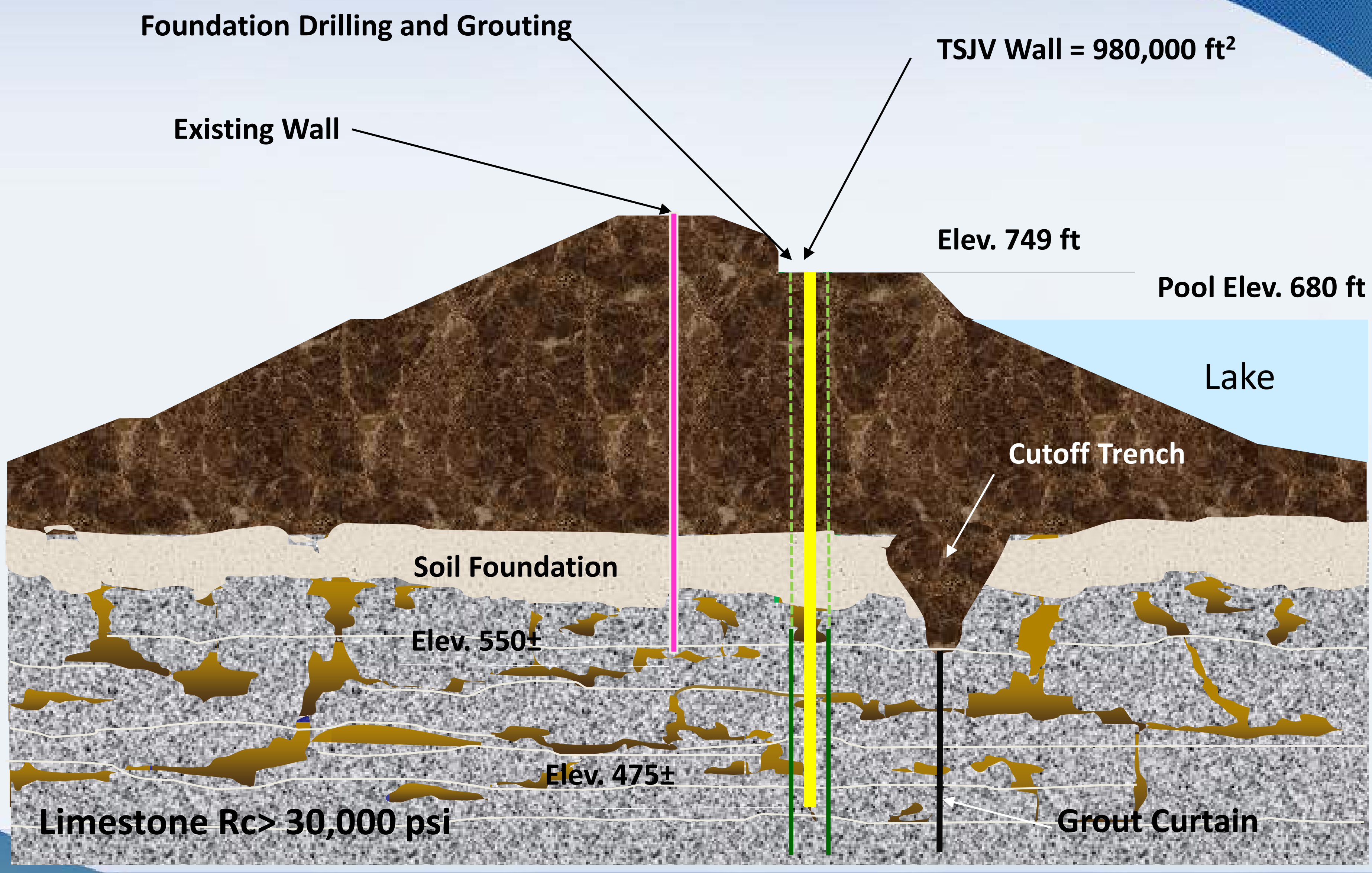
- By January, 2007, Wolf Creek Dam was judged to merit a DSAC-1 rating – therefore requiring urgent and compelling action. The justification was a return of the classic distress symptoms.

Increasing Distress Indicators



- Emergency grouting operation conducted as Phase 1 of the remediation in 2007-2008 by Advanced and Gannett Fleming as Phase 1 of a “Composite Wall” solution.
- Phase 2 involved the construction of a new cutoff upstream of the original, and longer and deeper, for an area of about 980,000 square feet – almost twice the original.
- Bid documents and specifications were Performance-based and emphasized Dam Safety in every process of the work, and urgency.
- It was obvious to all bidders that the technology of the 1970’s could not safely, reliably, or competitively satisfy the requirements of the 2008 project.
- The size, complexity and profile of the job attracted international attention from major prospective bidders.

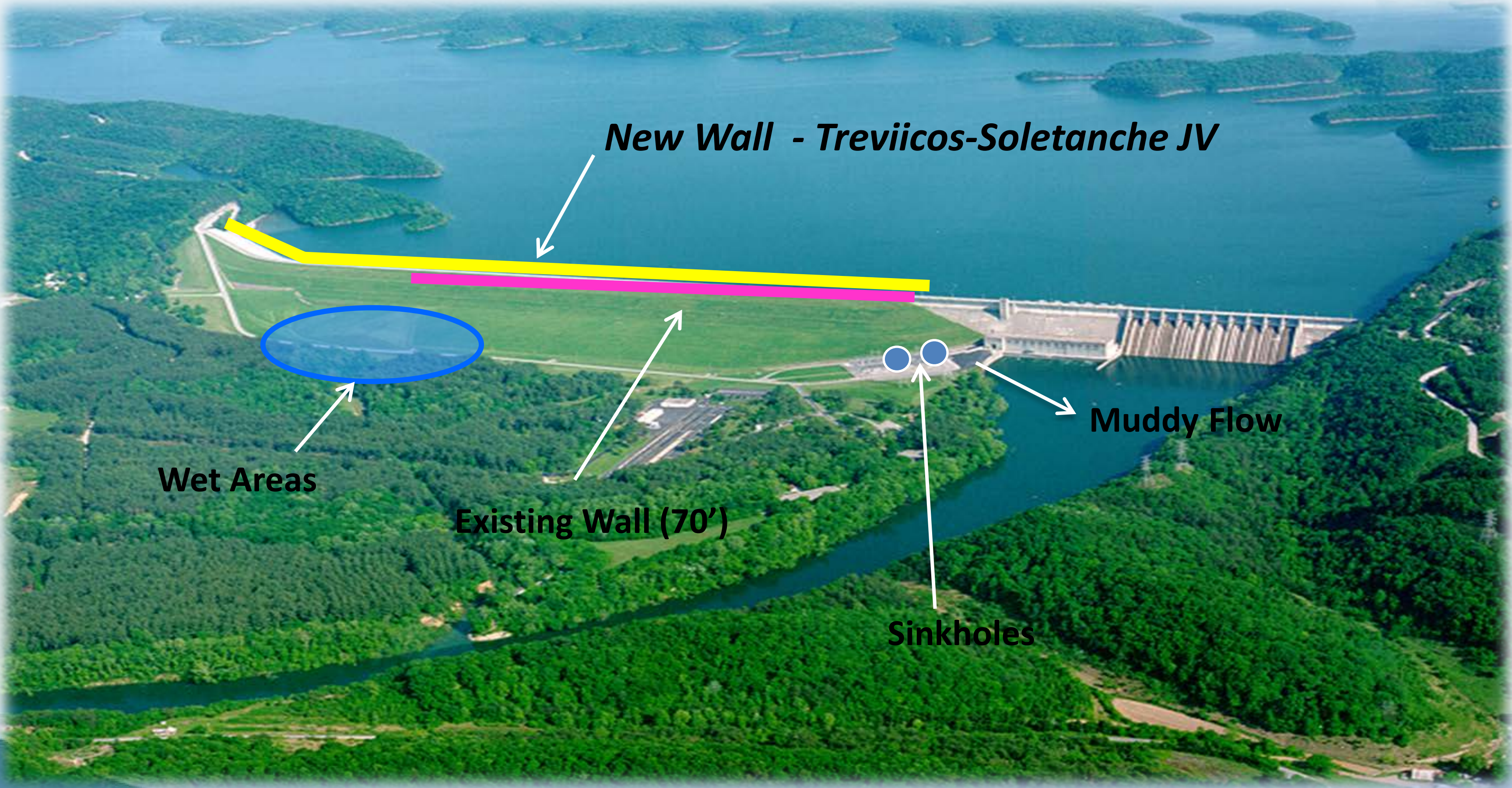
The Solution by USACE



3.2 Availability of the Technology

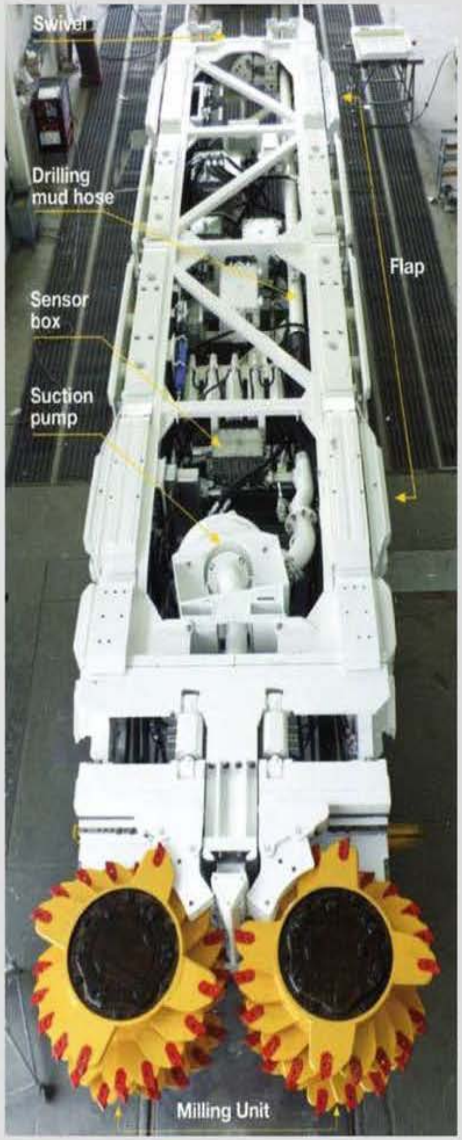
The Solution by the USACE

- Begins with 2-row grout curtain into rock (Advanced/Gannett Fleming)
- In late January 2007 → the USACE launches a $584 M remediation program
- In late 2008 → TSJV is awarded the main remediation contract for $341 M
- In the meantime → USACE maintains the pool elevation 80 ft below its maximum capacity



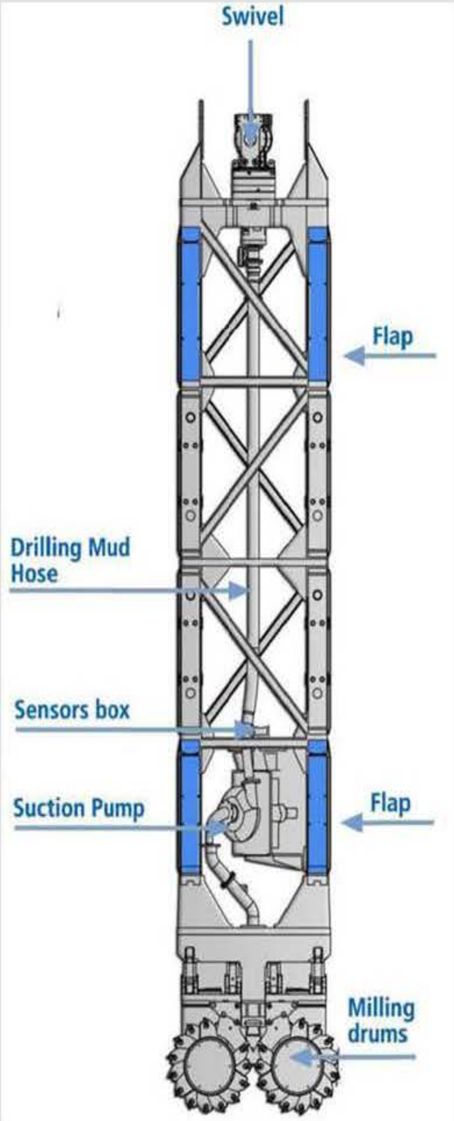
- The Trevi Group had acquired the ICOS Corporation of America in 1997, and had merged these assets with RODIO.
- TreviICOS had successfully conducted the cutoff at Walter F. George Dam, AL, from 2001-2003, principally leveraging expertise in large diameter secant pile technology (also used at Beaver Dam, AR, in 1992-1994).
- The Trevi Group also had particular expertise in directional drilling – essential for creating pilot holes with the specified 0.25% tolerance – and in Water-Powered, Down-the-Hole Hammer (Wassara).
- Soletanche – a pre-war French subsidiary of RODIO – now part of the Soletanche-Bachy Group, had patented in 1972 the hydrofraise (also known as a cutter or mill, by subsequent competitors).

HYDROMILL TECHNOLOGY



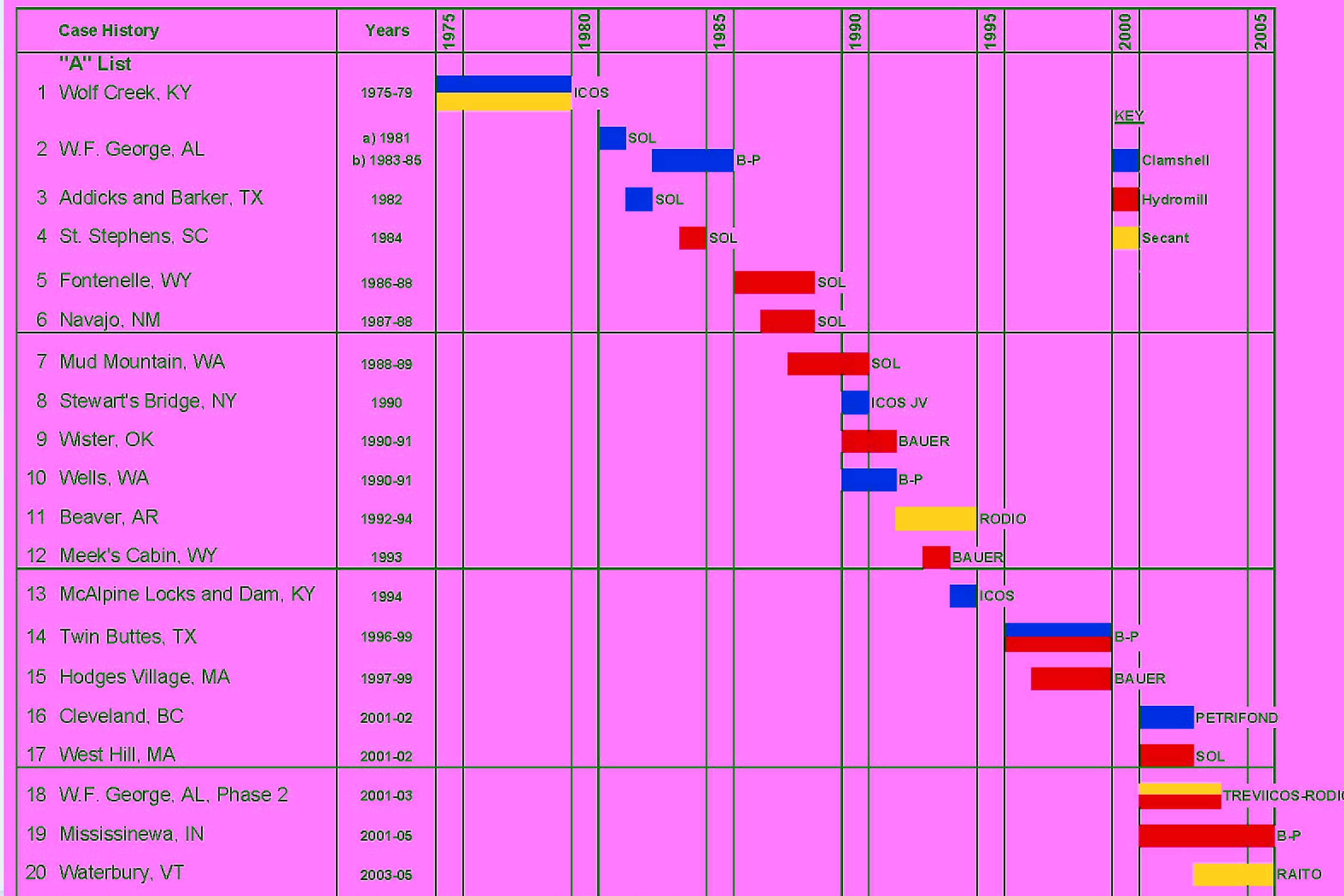
The core of any Hydromill is its trenching/cutting unit, that schematically consists of a heavy steel frame integrating the following components:

- 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.



- Initially deployed in Paris in 1973, a hydrofraise was first used for a dam remediation by Soletanche, Inc. at St. Stephen Dam, SC, in 1984 (110,000 square feet).
- Thereafter, it had been used (by other contractors also) on 8 other major dam remediations in the U.S. prior to 2008, totaling about 2.4 million square feet.

Project Listing Showing Chronology
Type of Cut-Off and Specialty Contractor

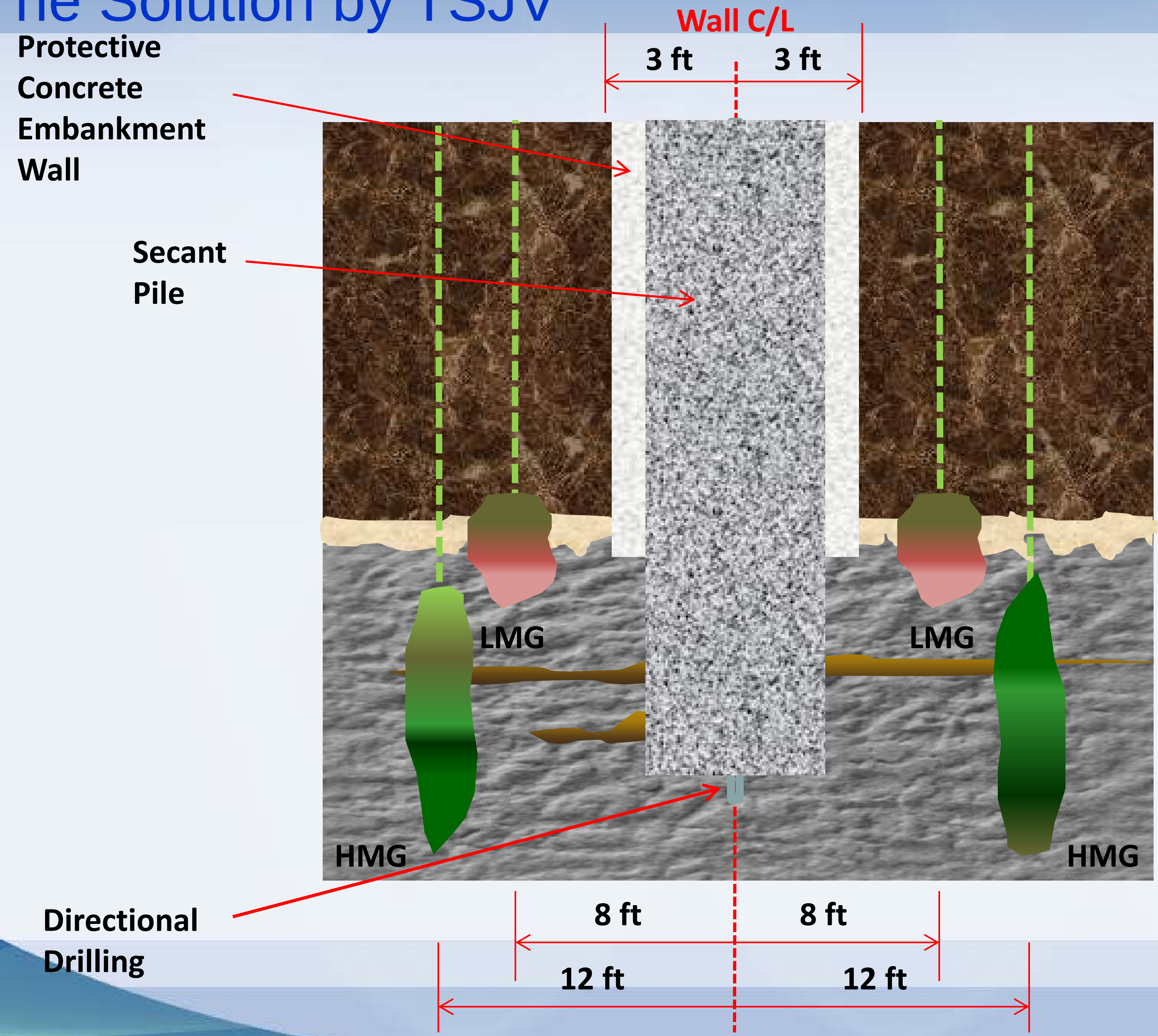


ICOS = TreviICOS
SOL = Soletanche Bachy
BAUER = Bauer Spezialteifbau GmbH
B-P = Bencor-Petrifond
RODIO = Rodio
PETRIFOND = Petrifond
RAITO = Raito, Inc.

- Hydrofraises had been used in remedial works to a maximum depth of over 400 feet (Mud Mountain Dam, WA) and have recently been tested to over 800 feet in a test at Gualdo, Italy, to within 0.13% verticality.

- Recent technological developments have focused on reliability, productivity, and verticality monitoring and control.
- The experience of the partners in Wolf Creek 2 was combined to provide the successful solution:
  - A 6-foot-wide, 535,000 sf “disposable” diaphragm wall constructed by hydromill through the embankment and just into the bedrock: the “Protective Concrete Embankment Wall” (PCEW), and
  - The actual cutoff created in the underlying karst by drilling 1,197 guided 50-inch diameter secant elements through the PCEW.

The Solution by TSJV



Embankment

Alluvium & Weathered Rock

Rock

Strength between 10,000 and 36,000 psi

Festures up to 40 ft in height

Mixed rock/soil conditions

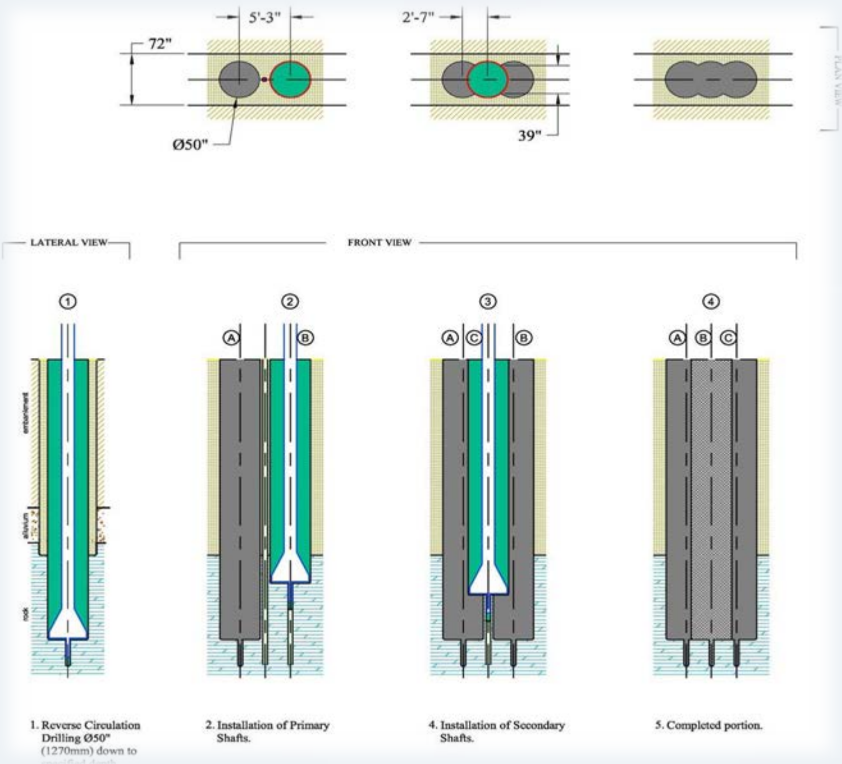
- Hayward Baker were engaged to explore and pretreat the potentially vulnerable embankment/rock contact with a LMG operation, and to thereafter extend the Advanced/Gannett Fleming grout curtain.

Protective Concrete Embankment Wall

Directional Drilling

Secant Piles

- Following the directional drilling pilot hole. 50” piles installed at 31.5” or 35” centers
- Ensuring the required overlap and minimum thickness. – Max target depth 277-ft



3.3 Owner Risk Acceptance

- USACE and the original Board of Consultants made an extraordinarily courageous decision to accept ICOS' proposal in 1975, and in effect bought 30 years of dam safety.
- USACE and the 2007 Board of Consultants were no less courageous in designing the second wall, given their superior insight about the fragility of the system.
- Risk mitigation measures were emplaced by the USACE:
  - "Best Value" award basis, with a focus on the Technical Proposal.
  - Successful execution of "Technique Demonstration Areas."
  - Very high levels of QA/QC and Verification.
  - Implementation of an intense Instrument Monitoring Plan.
  - Effective and efficient Partnering, and use of Board of Consultants, and Internal Advisory Panel (Contractor).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3.4 The Success of the Project

- Only 1 of the 1,197 secant piles fell outside the verticality criterion (installed early in a Technique Demonstration Area).
- All other criteria (strength, permeability, continuity, homogeneity) were satisfied.
- Project completed 9.5 months ahead of the revised construction schedule.
- No dam safety incidents were recorded (although pressure "transients" were noted during predrilling).
- Dam and foundation are functioning efficiently, predictably and stably.

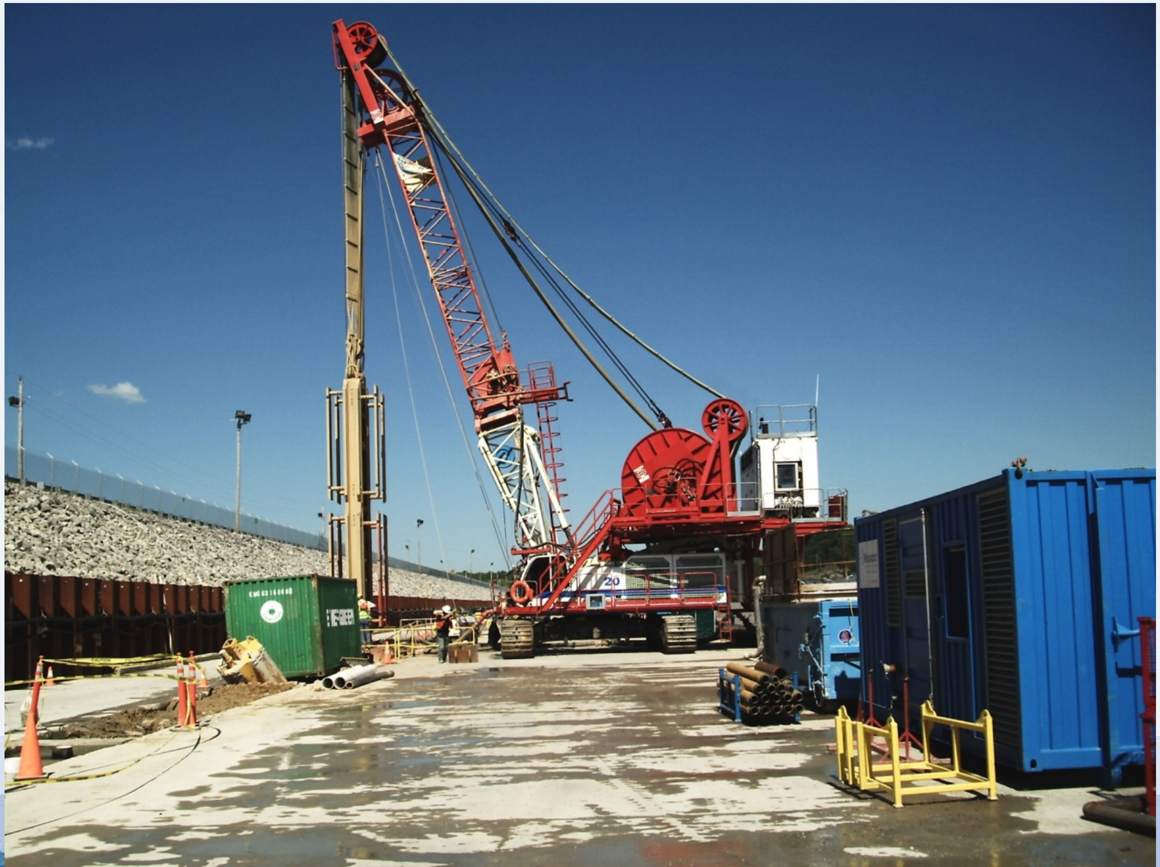
3.5 Technical Publications

- At least 12 technical publications from 2010 to May, 2014, in USSD, ASDSO and ICOLD Conferences.
- Further papers in international conferences in the U.S. and Europe.
- Numerous internal reports for the USACE and the Contractors.

3.6 Codification

- RMC of the USACE (David Paul) producing an Engineering Manual on cutoff walls for dams and levees, to enhance EM 1110-2-1901. To be published September, 2015.
- Bureau of Reclamation (Mark Bliss) finalizing new Design Standard on cutoff walls. To be published in August, 2015.
- DFI Slurry Walls Committee (Gianfranco DiCicco) developing a similar guideline on the application of specialty techniques for dam and levee remediation. Scheduled for 2016.
- All of these will provide “new blood” for the existing ICOLD Bulletin 150, and the European Standard EN1538.

- Also noteworthy that the "lessons learned" from Wolf Creek 2 have been incorporated into subsequent USACE documents for cutoffs at Center Hill Dam, TN; East Branch Dam, PA; and Bolivar Dam, OH. These specifications have therefore become more Prescriptive.



5. FINAL REMARKS

- For each of the three techniques/applications detailed in the paper, satisfaction of each of the six defining criteria is proved:
  - For Drilling and Grouting: The “Great Leap” comprised a group of major developments in processes, materials, technology platforms and design concepts. Implemented under the vision of one contractor/consultant team in response to a major market need.

- <u>For Concrete Cutoffs</u>: The “Great Leap” had 3 steps:
  - the initial acceptance that a diaphragm wall was a safe and feasible solution for dam remediation (Wolf Creek 1);
  - the development of the hydromill; and
  - the technological advances made in response to extraordinary technical and dam safety challenges (Wolf Creek 2).

- For Deep Mixing: The “Great Leap” of 2008 comprised two parallel strides in huge, concurrent projects for USACE:
  - The implementation of a newly imported technology (TRD) at Herbert Hoover Dike, FL;
  - A group of major enhancements to a traditional technology (TTM) at LPV 111, New Orleans, LA.

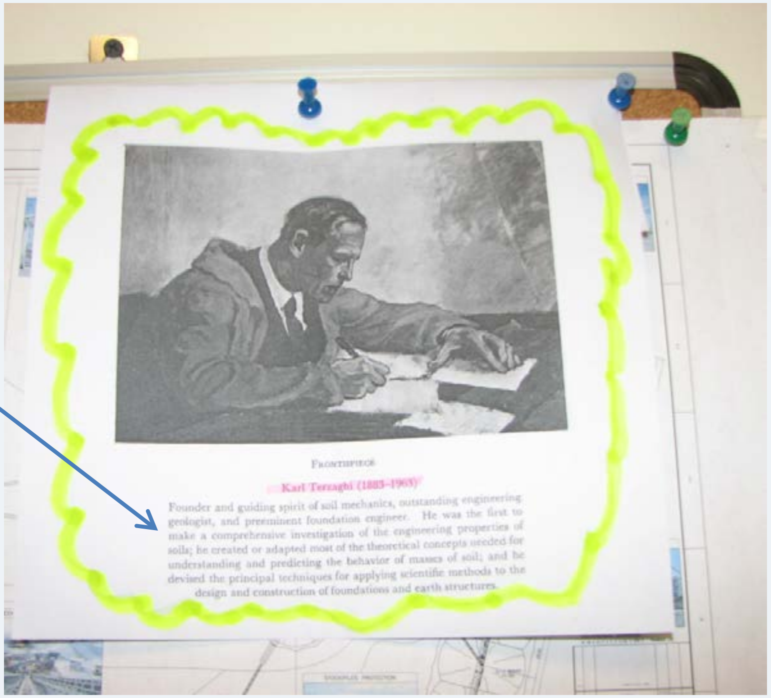
- Each “Great Leap” was engineered to satisfy the demands of a specific project (or group of related projects) of unprecedented scale and urgency, and each was facilitated by the use of innovative procurement vehicles by the Federal Government.

- Each “Great Leap” has been widely published and the outcome incorporated in new Design and Practice Manuals and Guidelines, and has been adopted (as far as Patents permit) by industry at large.

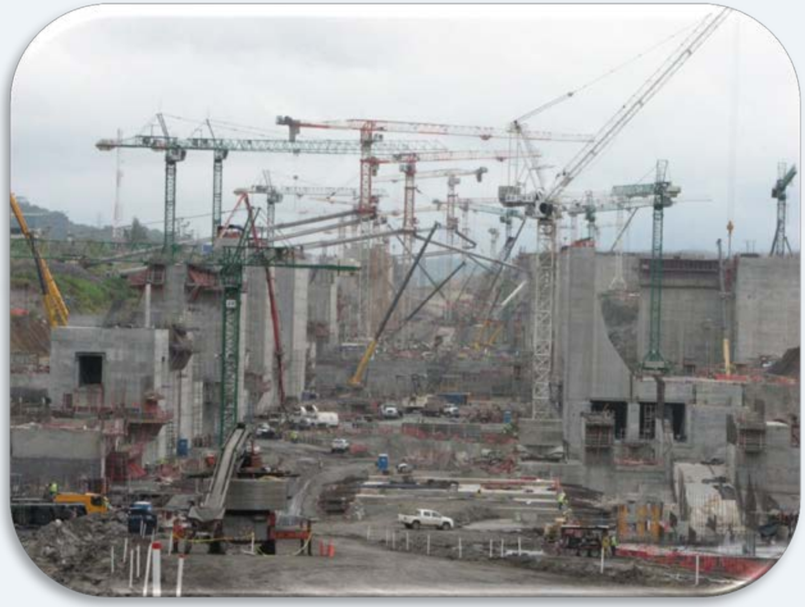
This image is taken from the seminal textbook "Foundation Engineering" by Peck, Hanson and Thornburn (1974).

"*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."

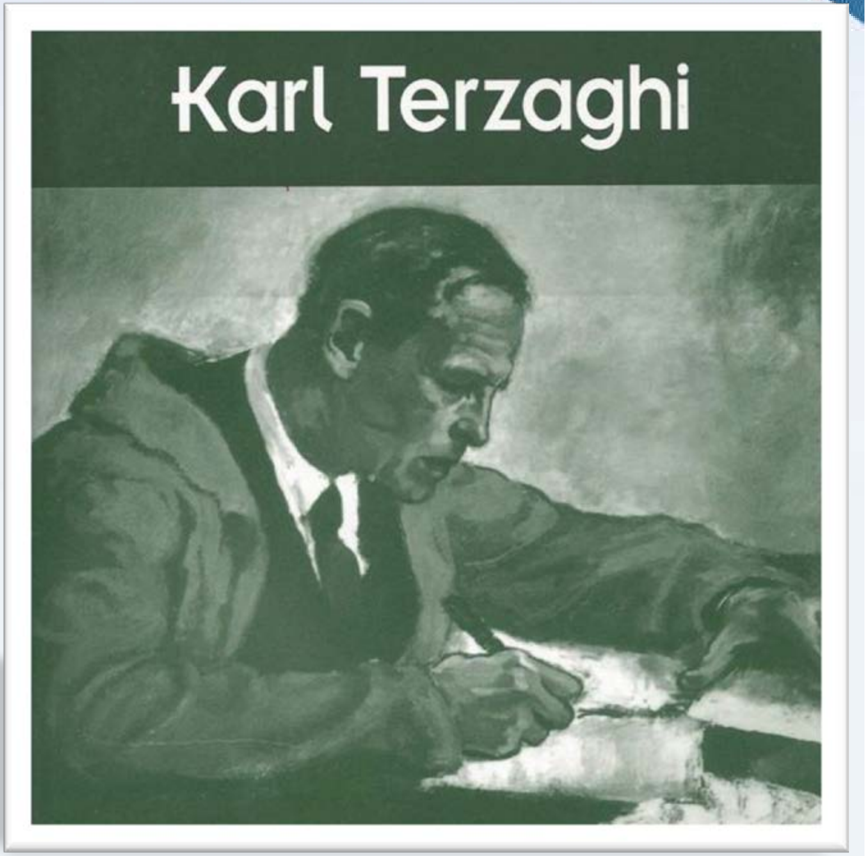


- The image was not taken from the Goodman textbook, but was sent at my request by Rick Robertson of CH2M Hill International – Panama (Leader of Locks Dispute Team for the Third Locks Project).
- He sent this photo of a photo of a drawing he had tacked to his office wall under the following cover:



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

- So, the real legacy of Prof. 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.



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- The wonderful work on the graphics was undertaken by my Personal Assistant, Mrs. Terri Metz.
- The time to prepare this presentation was donated by my family.
- My thanks to all of you who chose to attend this presentation, and to the AEG for extending the invitation to give it.
- The wonderful efforts of Dr. Brian Greene of Gannett Fleming on behalf of AEG, and all his growing army of helpers.

Thank You!