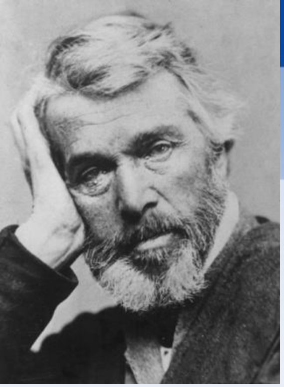
THE EVOLUTION OF SPECIALTY GEOTECHNICAL CONSTRUCTION TECHNIQUES: THE “GREAT LEAP” THEORY

GeoVirginia 2016

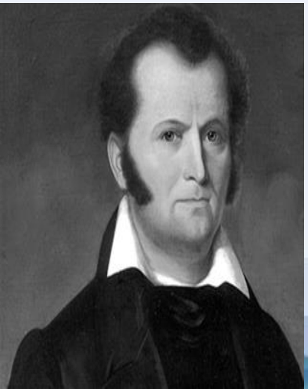
Donald A. Bruce - Geosystems, L.P.

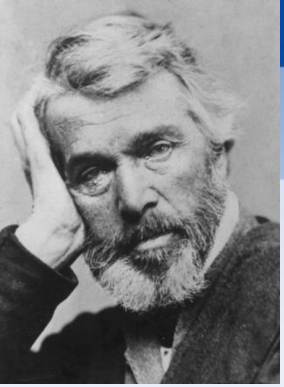
Terzaghi Lecture
October 11, 2016



1. DEVELOPMENT OF THE BASIC THESIS

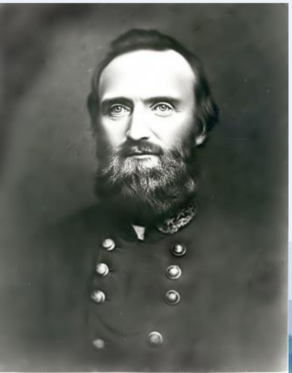
- Carlyle’s “Great Man” Theory of History
- “Great Men” in Geotechnical Engineering Practice: The Terzaghi-Goodman-Peck Triangle, and Others
- “Great Leap” Theory Applies for Geotechnical Construction Techniques

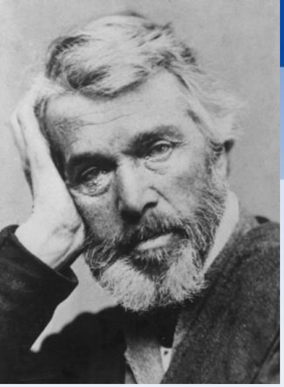




- “Great Leap” Theory demands the satisfaction of six successive criteria:

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 was demonstrated in my original Terzaghi Lecture by analyzing progress in 3 processes in particular:
  - 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).

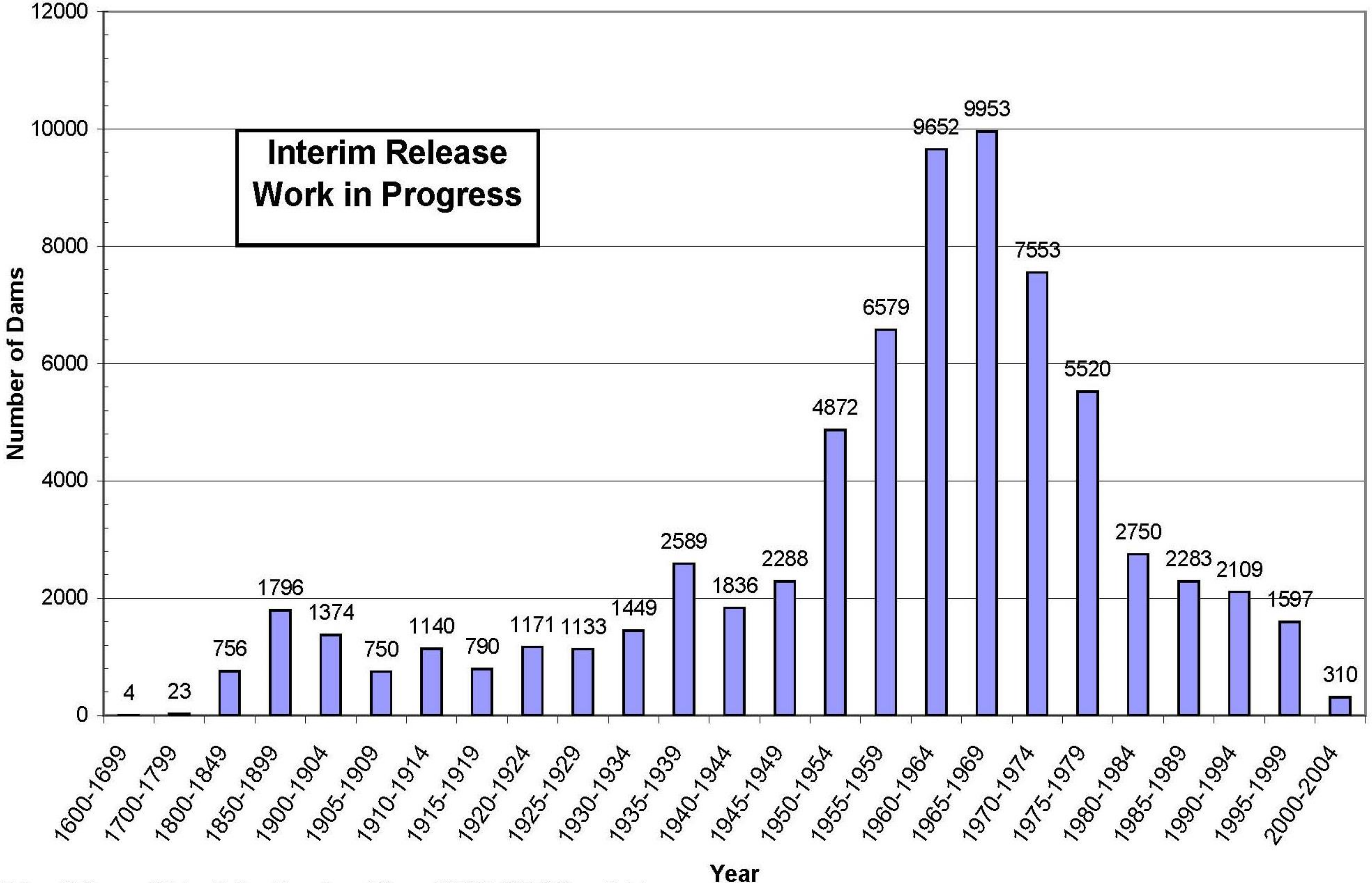
- This morning we have time only for Grout Curtains in Rock.

Fundamental challenges are posed to our dams and levees by:

- Geology: 40% of contiguous states underlain by evaporites/karst

- Seismicity: New Madrid, MO and Charleston, SC, as well as Western U.S.
- Aging/maintenance funding
- Natural disasters

Histogram of US Dam Construction (1600-2004)



Notes: 1) Source of Data - National Inventory of Dams, USACE, 79777 Dams Total
2) Does not include 9500 dams where the year construction completed is not reported or invalid
3) Total number of dams (not including 9500 with unreported/invalid data) = 70277

2. GROUT CURTAINS IN ROCK

2.1 The Exceptional Nature of the Project

- It is more appropriate to consider a *group* of projects 1997-2007 involving deep remedial curtains in karstic limestone.

- Pre-Leap Practices
  - Highly prescriptive specifications.
  - Almost complete absence of rational design and acceptance processes and widespread use of “rules of thumb” for design and execution.
  - Use of:
    - vertical holes to a predetermined depth
    - single row grout curtains
    - long downstages of predetermined length
    - rotary drilling (percussion = air flush)
    - low and conservative grout pressures
    - “thin” grouts
    - “dipstick, gage and stopwatch” methods for injection control
    - termination of work based on grout takes (and/or cost).

- Pre-Leap Practices (continued)
  - These archaic practices were totally unsuited to the 1997-2007 demands with respect to logistics, performance and dam safety.

(Courtesy of California Department of Water Resources)

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.

2.2 Availability of the Technology

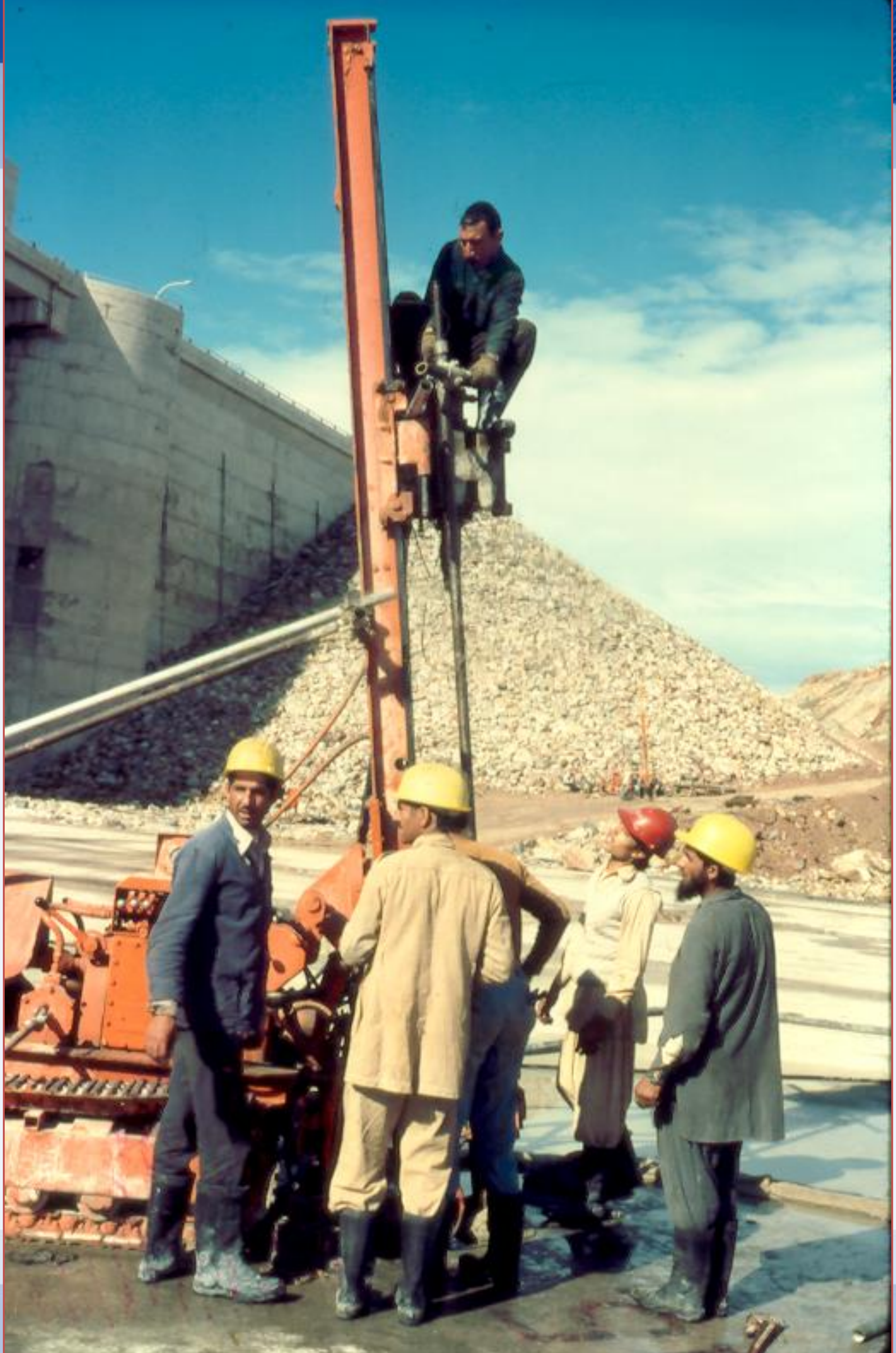
- Market conditions/industry inertia up until mid-1990's were generally against new technologies. Notable exceptions were USACE/ Reclamation at Ridgway Dam, CO, and Upper Stillwater Dam, UT, and the initial promotion of GIN Theory.
- Technology was totally changed after the association of Advanced Construction Techniques, Toronto, ON (Contractor) and Gannett Fleming, Inc., Harrisburg, PA (Consultant).
- They simultaneously introduced numerous technical developments – as an integrated package – and design concepts (e.g., Quantitatively Engineered Grout Curtains) at a time when the USACE was moving towards "Best Value," as opposed to "Low Bid," and more Performance-based Specifications.

- Notes:
  1. The associated design improvements included:
     - multirow curtains;
     - inclined holes in each row;
     - depth of curtain determined by geology and/or by rigorous seepage analyses;
     - stage lengths commensurate with the structural geology;
     - use of the highest safe grouting pressures;
     - verification of proper stage refusals;
     - verification of residual in-situ permeability upon closure.

- Major technological developments were incorporated into all the important processes:
  - Drilling
    - Design and construction of new generation drilling rigs (Cubex).
    - Use of sonic drilling and double-head dry duplex for overburden drilling (Boart Longyear/Advanced).
    - Use of water-powered down-the-hole hammer (Wassara) for rock drilling.
    - Routine use of automated “Measurement While Drilling” instrumentation (Lutz and others).
    - Routine use of hole deviation monitoring (Robertson Geologger and others).

Photo No. 30. Drilling curtain holes through concrete at Elevation 188 in monolith 19. View downstream.
Neg. No. OD 6186 2-4-65

(Courtesy of California Department of Water Resources)




QXW1210
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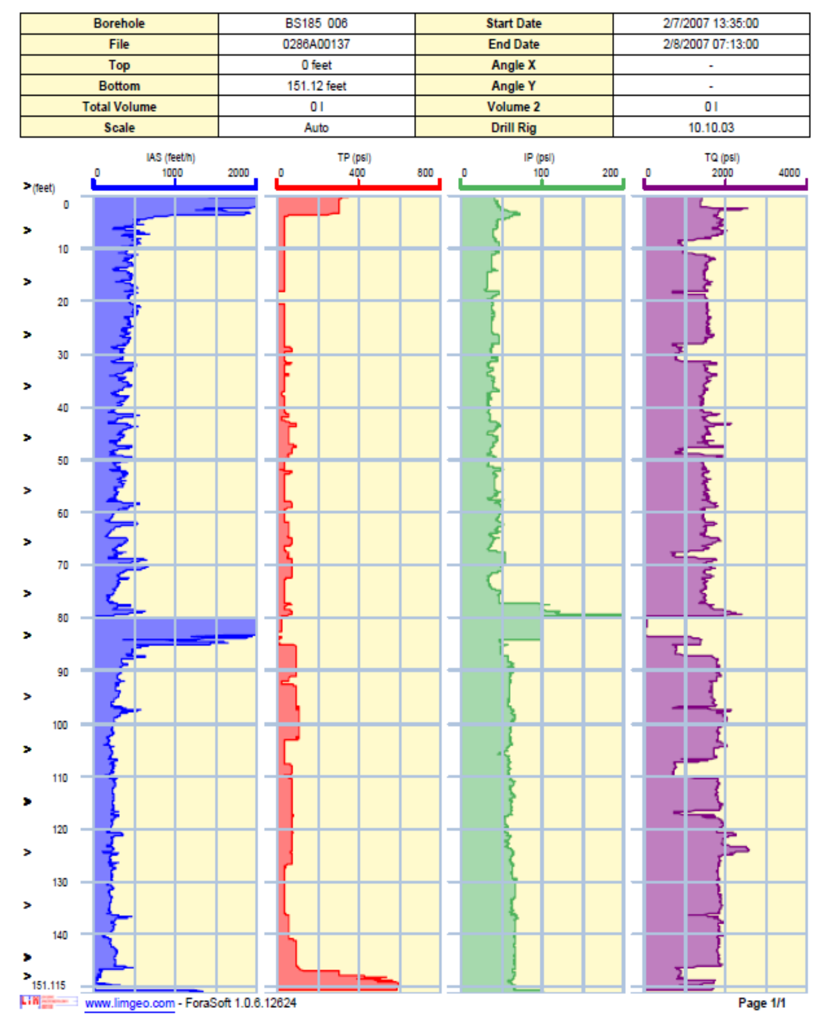
CUBEX


4:43PM

Water Powered DTH

Monitoring While Drilling (MWD)



Borehole	BS185 006	**Start Date**	2/7/2007 13:35:00
File	0286A00137	**End Date**	2/8/2007 07:13:00
Top	0 feet	**Angle X**	-
Bottom	151.12 feet	**Angle Y**	-
Total Volume	0 l	**Volume 2**	0 l
Scale	Auto	**Drill Rig**	10.10.03

www.limgeo.com - ForaSoft 1.0.6.12624

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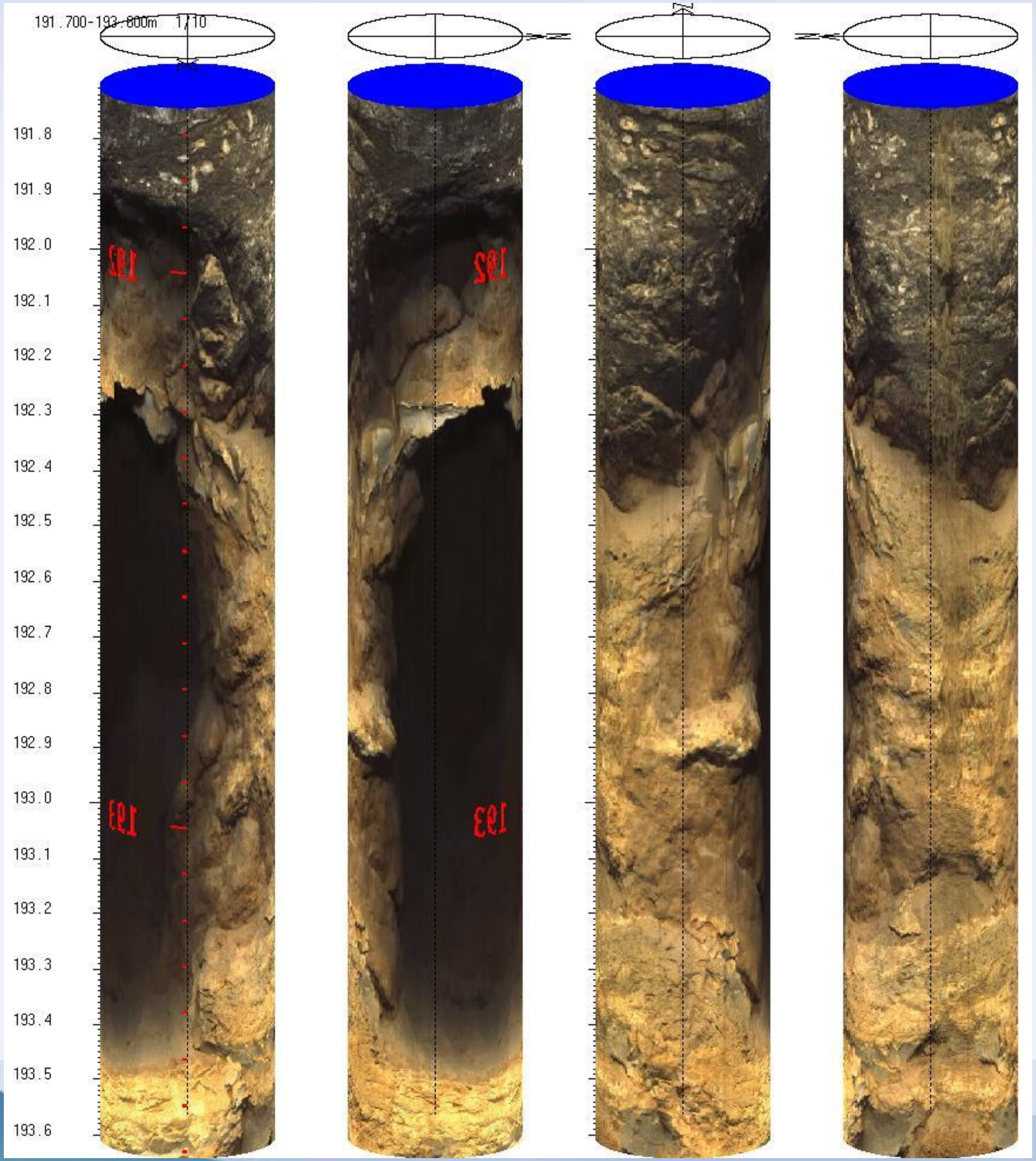
Robertson GeoLogger System

High Resolution Borehole Imaging



S36.70U
192.3’ - 193.4:
Solution feature in
Leipers Fm.

Wrapped image
suggests feature trends
NW-SE, normal to dam.

- Injection Systems
  - Grout “buggies.”
  - Automated grout batching and mixing in weatherproofed enclosures.

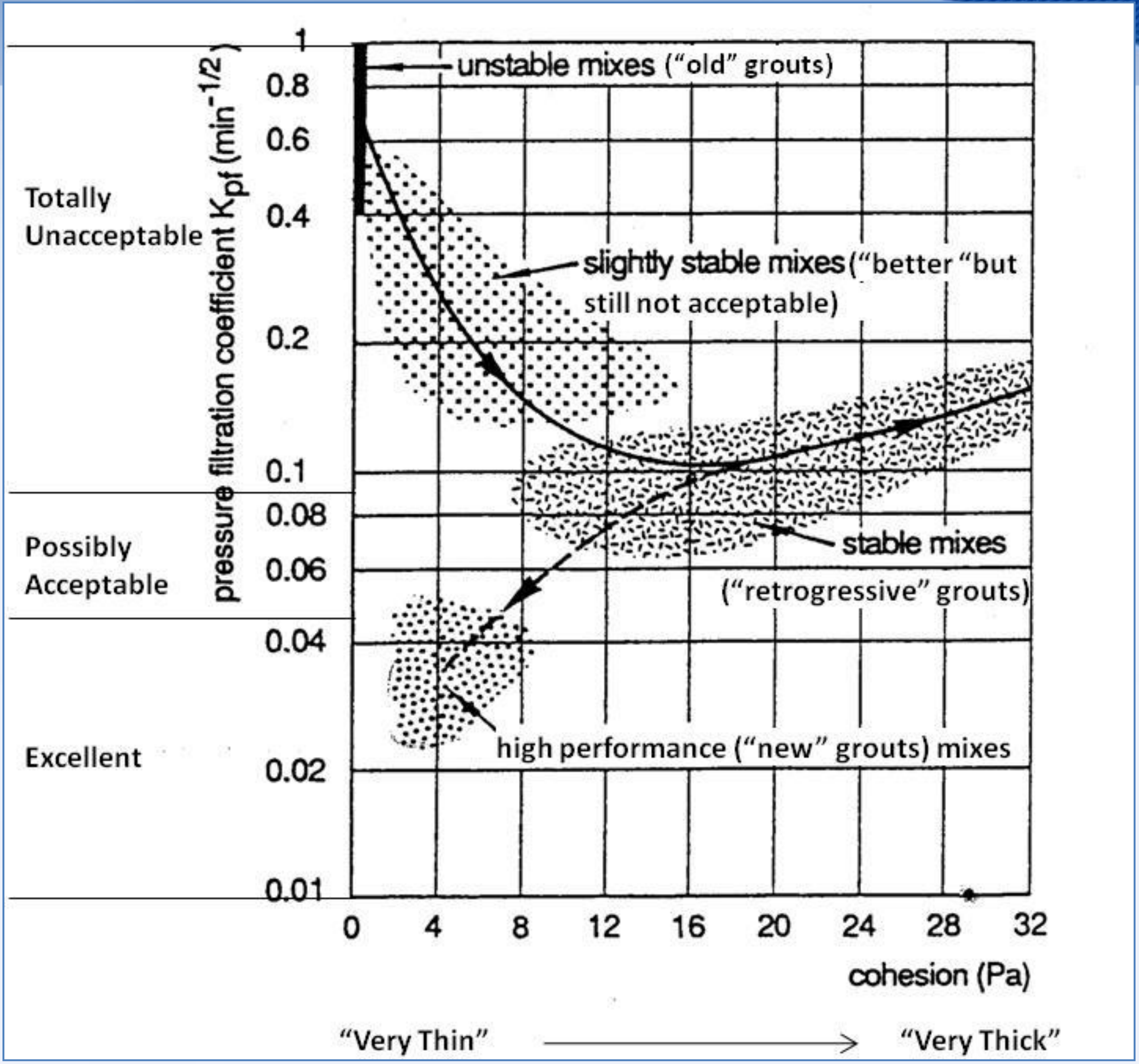
- Grout Mixes
  - Development of balanced, stable multicomponent grouts giving superior rheological properties (Naudts, Master Builders, Sherrill).
  - In particular, exploiting a full understanding of the importance of the pressure filtration coefficient (DePaoli et al.)

Photo No. 31. Grouting equipment. High speed, double drum grout mixer is on right; agitator is on left. Grout pump is behind agitator. View towards left abutment.

Neg. No. OD 14592 2-15-67

(Courtesy of California Department of Water Resources)

Monitoring Equipment



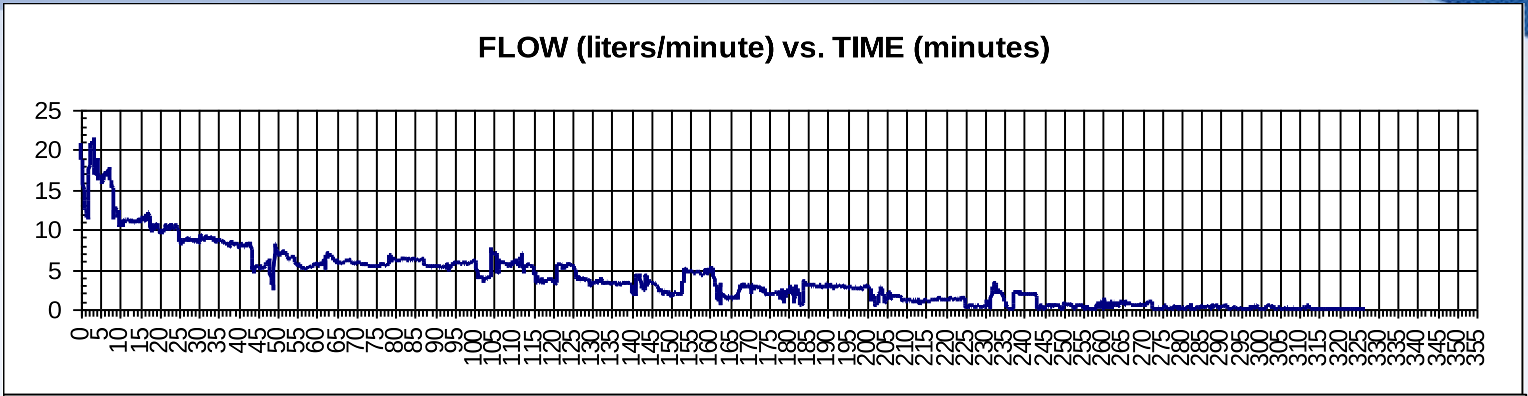
Historical path of development from unstable mixes to contemporary balanced multicomponent mixes (modified after DePaoli et al., 1992).

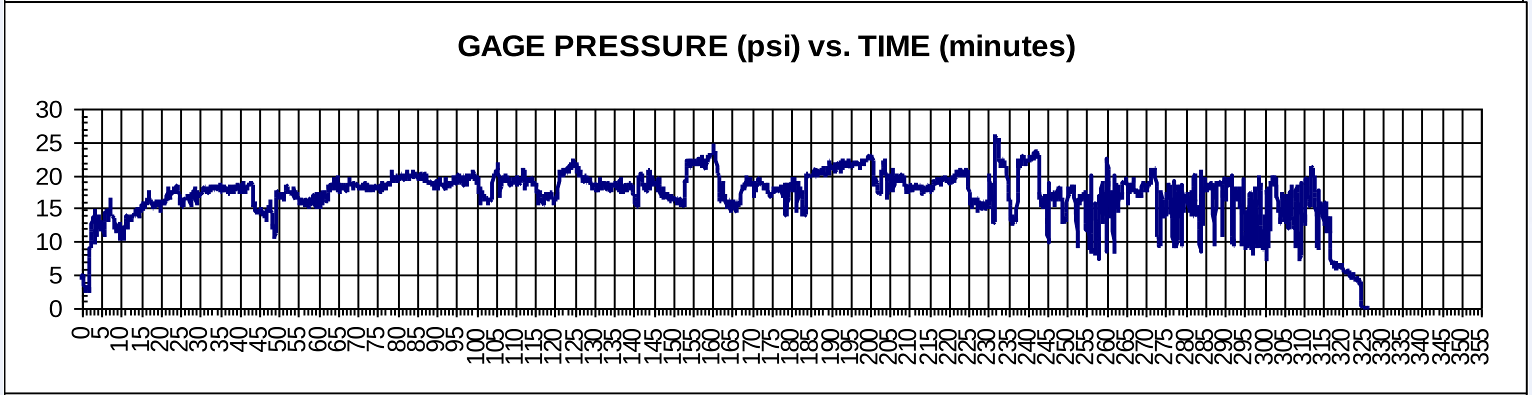
- Computer Control and Analysis
    - First CAGES (ECO Grouting), soon modified to “Intelligrout,” to record, analyze, control and display all injection parameters in real time.
    - Use of Apparent Lugeon Theory (Naudts) predicated on development of stable mixes.

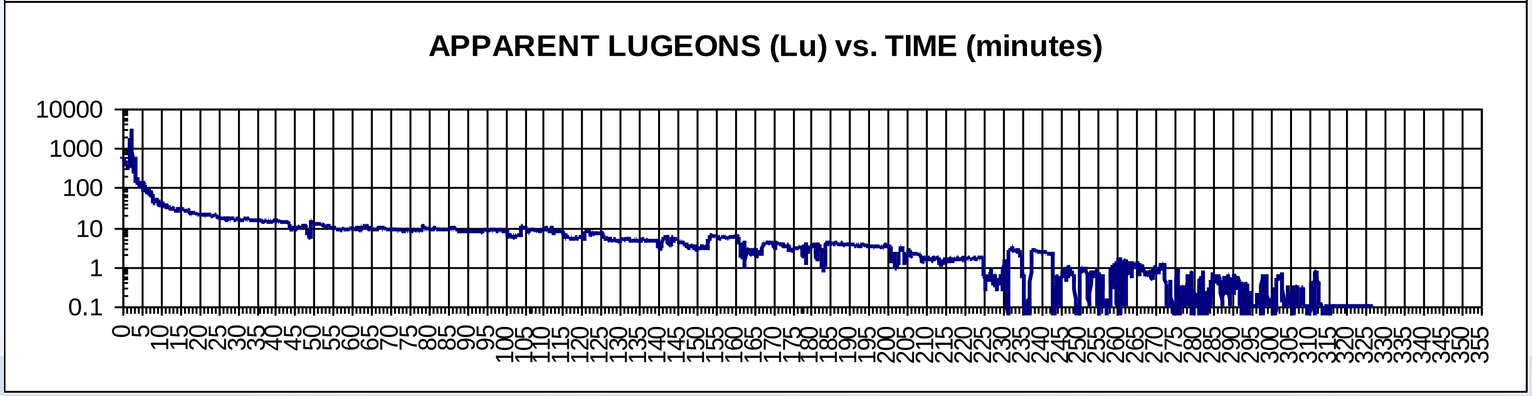
- Verification
    - Use of “Intelligrout” in real time (Advanced/Gannett Fleming).
    - Systematic use of multipressure Lugeon testing in Investigation and Verification Holes (Houlsby).
    - Systematic use of Optical Televiewer to show in-situ rock conditions without actually coring (Robertson).


ION

Level 3 Computer Monitoring System


FLOW (liters/minute) vs. TIME (minutes)


GAGE PRESSURE (psi) vs. TIME (minutes)

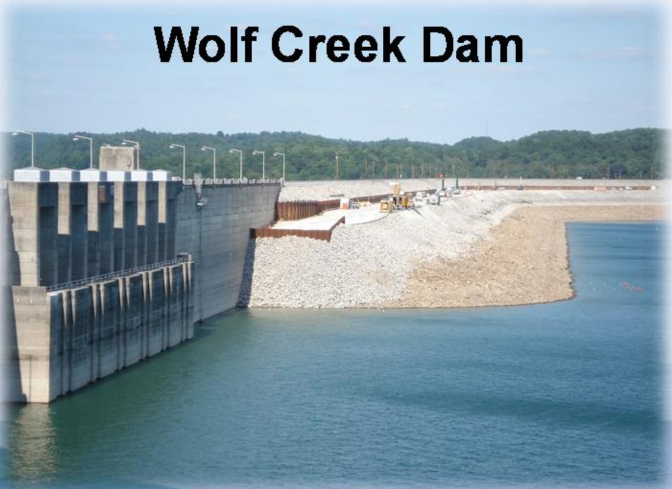

APPARENT LUGEONS (Lu) vs. TIME (minutes)

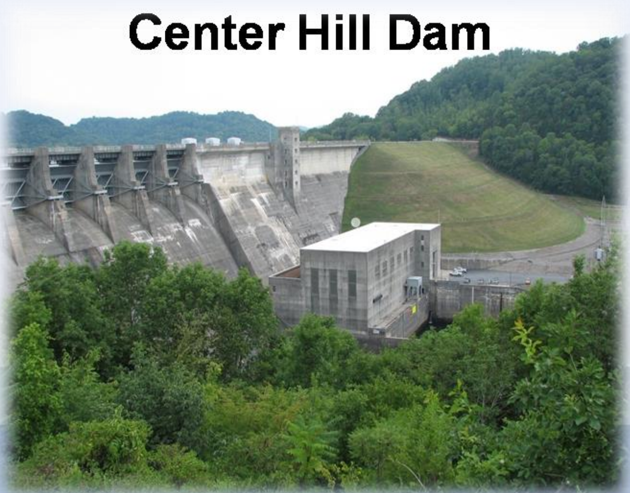
Water Lugeon Value = 100

2.3 Owner Risk Acceptance

Post-Leap

- First two projects had non-Federal clients (City of Bethlehem for Penn Forest Dam, PA, and County of Spotsylvania for Hunting Run Dam, VA). They and the Engineer-of-Record (Gannett Fleming, Inc.) accepted and shared the "novelty risk."
- For the later projects, the USACE accepted the "novelty risk," especially the Louisville, Little Rock, Nashville, and Chicago Districts, and Headquarters.


Wolf Creek Dam


Center Hill Dam

2.4 Success of the Project

- Curtains were systematically engineered to satisfy the in-situ residual permeabilities required by the design (1-5 Lugeons).
- Every project has provided compliant results.
- Curtains used as integral part of the "Composite Wall" concept to explore and improve the rock before construction of a concrete diaphragm wall between the outer rows. Every such project has been successfully and safely completed.

2.5 Technical Publications

- Proc. International Conferences on Grouting and Deep Mixing (Geo-Institute), New Orleans, 2003 and 2012.
- Proc. Annual Conferences ASDSO and USSD.
- Textbooks (Weaver and Bruce, 2007; Bruce, 2012).
- Annual Short Course on Grouting at Colorado School of Mines.
- Presentations at USACE's Infrastructure Conferences.
- Several other Contractors have been regularly using the "new methods" over the last 10 years with excellent results.

4th International Conference on Grouting and Deep Mixing

Organized by: International Conference Organization for Grouting

INTERNATIONAL CONFERENCE ICOG ORGANIZATION FOR GROUTING

Managed by: Deep Foundations Institute

DEEP FOUNDATIONS INSTITUTE DFI

New Orleans, Louisiana, USA
February 15-18, 2012

36TH ANNUAL SHORT COURSE

Grouting Fundamentals and Current Practice

JUNE 22-26, 2015
COLORADO SCHOOL OF MINES

COLORADOSCHOOLOFMINES.

2.6 Codification

- Complete revision, by Gannett Fleming, under contract of the USACE’s Grouting Technology Manual (EM-1110–2-3506) of 1984.
- Issued by USACE on July 31, 2014.

5. FINAL REMARKS

- For each of the three techniques/applications presented, satisfaction of each of the six defining criteria is proved:
  - <u>For Drilling and Grouting</u>: 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.

- For Concrete Cutoffs: 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:
  - The implementation of a newly imported technology (TRD); and
  - A group of major enhancements to a traditional technology (TTM).

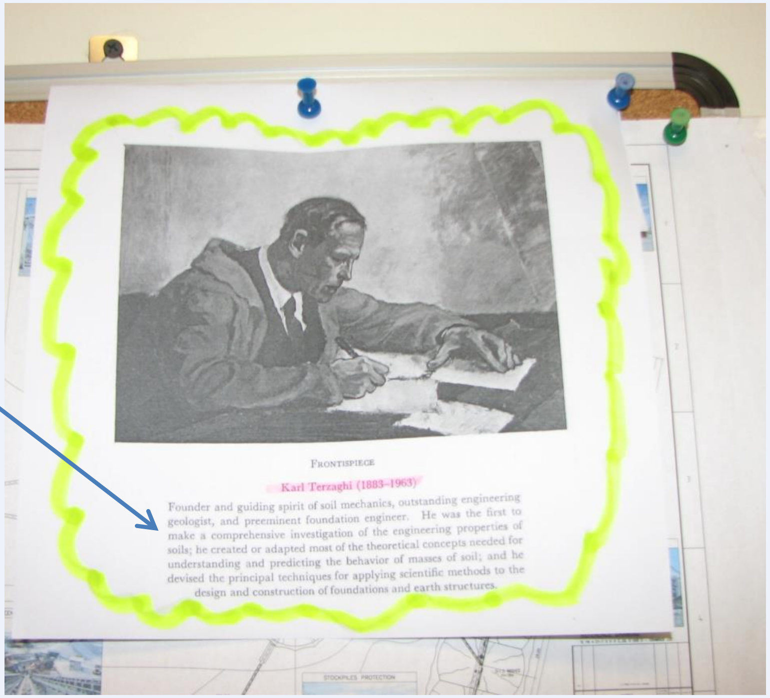
- Each “Great Leap” was engineered to satisfy the demands of a specific project (or group of related projects) of unprecedented scale and urgency, and each was facilitated by the use of innovative procurement vehicles by the Federal Government.

- 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.”



FRONTISPIECE

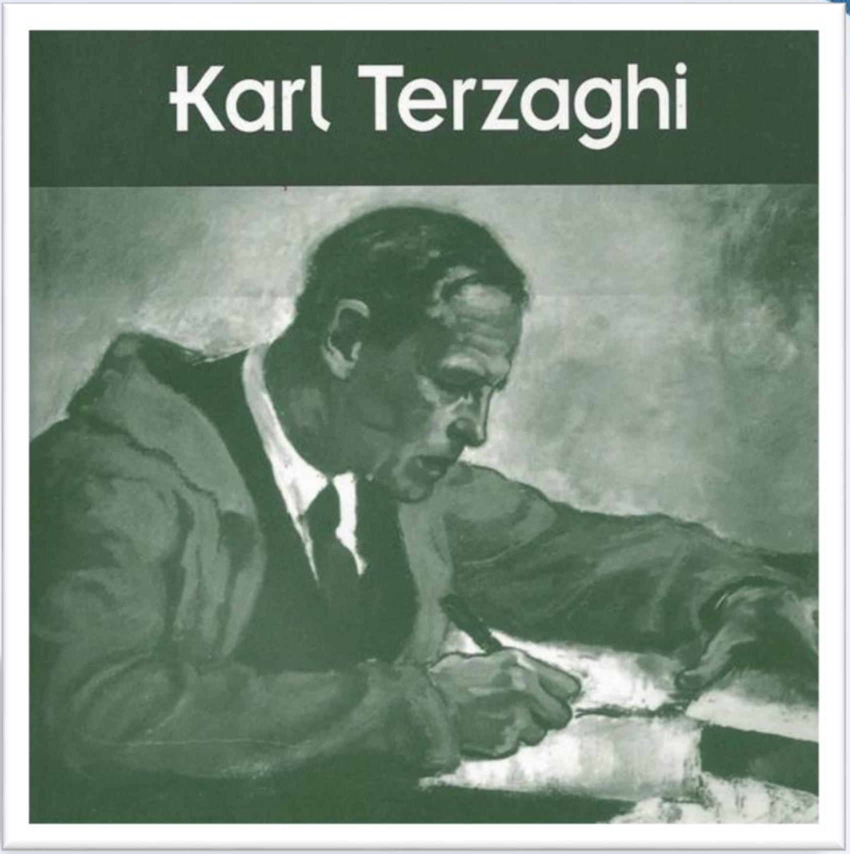
Karl Terzaghi (1883–1963)

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 by Mrs. Metz from the 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, what are the lessons learned about 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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Mary Ellen Large

Tom Richards

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- The wonderful work on the graphics was undertaken by my Personal Assistant, Mrs. Terri Metz.
- My thanks to Qamar Kazmi for organizing this event.
- My thanks to all of you who chose to attend this presentation, and my hope that you enjoy the Conference.