RCC 2015 – International RCC Dam Seminar and Duck River Reservoir Study Tour

RCC DAM FOUNDATION SELECTION AND TREATMENT

Donald A. Bruce, Ph.D., D.GE, C.Eng., P.G. L.G., L.E.G.
GEOSYSTEMS, L.P.

RCC 2015 35 YEARS OF COLLABORATION

Geo-Trust

OUTLINE

1. Site Selection
2. Foundation Evaluations – General Comments
3. Foundation Investigations
4. Foundation Evaluations and Analyses
5. Foundation Surface Preparation
6. Foundation Drilling and Grouting
7. Final Remarks

1. SITE SELECTION
1.1 Valley Shape

- Probably the most important factor
  - Volume of the dam
  - Function of the hydrologic and geologic conditions

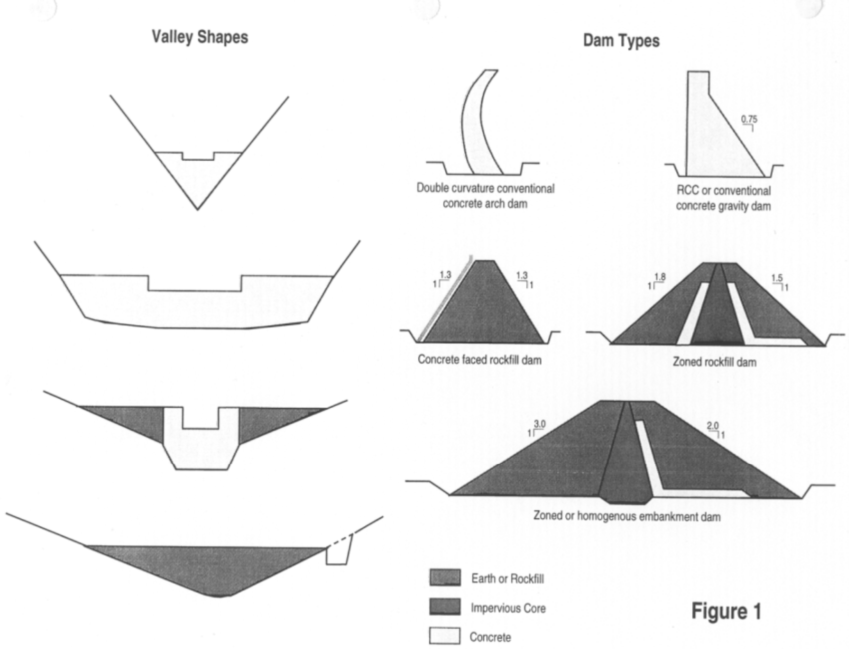


Figure 1

From Moler, 1998

1.2 Foundation Conditions

- Depth to sound bedrock (suitable foundation)
  - Thickness and characteristics of alluvial deposits
  - Weathering characteristics of rock
- Uniform and smooth geometry of foundation surface
- Foundation treatment requirements

1.3 Proximity to Suitable Construction Materials

- Roller-compacted concrete aggregates
  - Quality
  - Quantity
  - Soil Deposits vs. Quarry
  - Processing
  - Commercial Sources
- Cement
- Fly ash
- Water

2. FOUNDATION EVALUATIONS: GENERAL COMMENTS

To avoid the shortcomings associated with present practice requires first of all **expert translation of the findings of the geologist into physical and mechanical terms**. Next it requires the **evaluation of the most unfavorable mechanical possibilities which would be expected under the existing geologic conditions**; and finally to **assume** for the design of the structure the **most unfavorable possibilities**. These mental operations represent by far the **most important, most difficult, and most neglected tasks** in the field of dam foundations.

Approximately 70 percent of concrete dam failures (gravity and arch) can be attributed to geological or geotechnical problems.

ICOLD, 1974

Primary Causes of Dam Failure

- Missing team attributes
- Failure to understand/appreciate foundation failure modes and to collect data, perform evaluations, and provide appropriate design provisions for these failure modes

Seven Attributes of Successful Foundation Evaluations
(after Stapledon)

- Knowledge and Experience of Team in:
  - Precedents (Successful and unsuccessful case histories)
  - Engineering Geology
  - Soil and Rock Mechanics
  - Civil Engineering Design
  - Civil Engineering Construction
  - Direct and Indirect Exploratory Methods
  - Above Average Application

Foundation Objectives

- Adequate Bearing Capacity/Deformation
- Adequate Seepage Provisions
  - Quantity
  - Drainage/Uplift
- Adequate Piping
- Adequate Sliding Stability
- Other
  - Toe Erosion

Foundation Failure Mode Identification

- Irregular Deformation
- Sliding along Discontinuities
- Blowout (piping) of Weak Rock or Seams
- Washout of Foundation due to Overtopping
- Landslide-Induced Waves
- Undermining of Spillway due to Washout

3. FOUNDATION INVESTIGATIONS

Common Foundation "Bad Actors" (after Deere, 1981)

- Thin Shear Zones (bedding, foliation)
- Solution Features in Soluble Rock (Limestone, Marble, Gypsum)
- Fault Zones Causing Potential Sliding
- Weak, Continuous Joint Sets
- Weathered Bedrock (excavation quantities and stability)
- Volcanic Rock (erratic competency and buried paleo-features)

Importance of Good Data Collection

- Forms the input parameters for the foundation evaluations and design
- The results of the evaluations depend on the quality and reality of the data as compared to the actual conditions they are intended to represent.
- Garbage in/Garbage out

Requirements of Good Data Collection

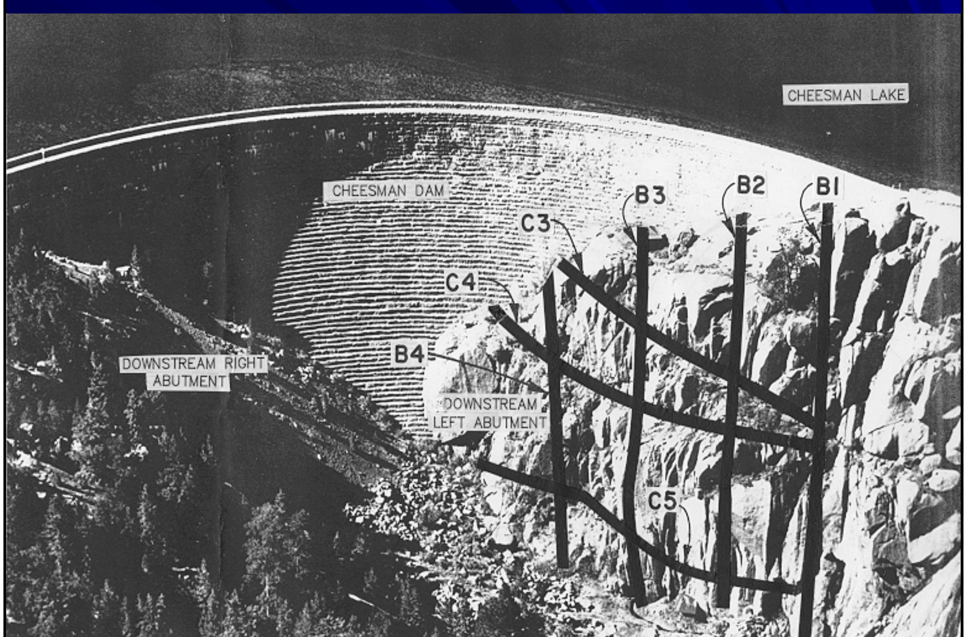
- Understanding of Knowns and Unknowns
  - Background information
  - Site conditions
  - Data collection limitations
  - Site constraints
  - What if’s
- Defining/Assessing Variability and Uncertainty
- Focused/Deliberate Effort to Gather the Data Needed
- Experienced/Knowledgeable Data Gatherers

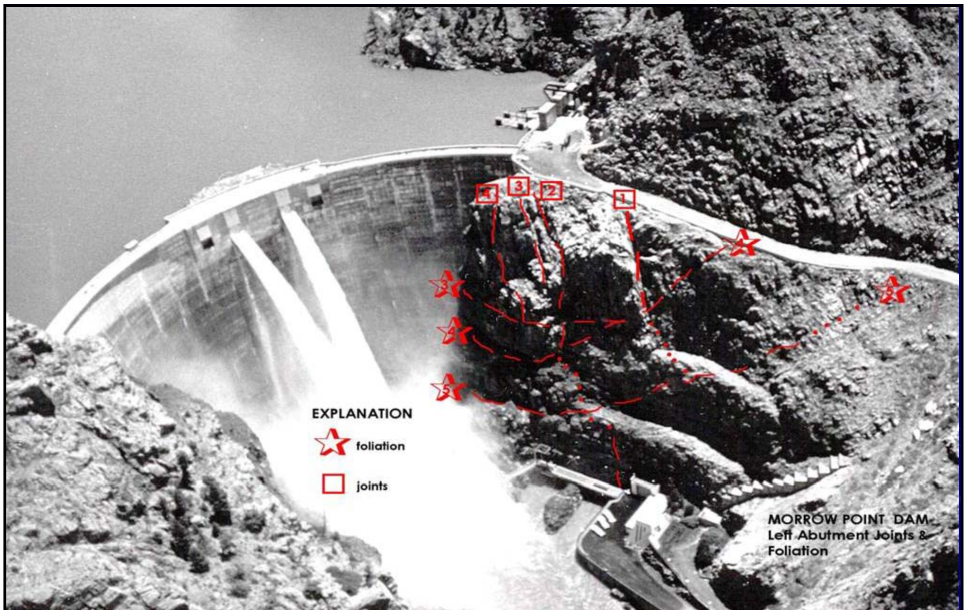
4. FOUNDATION EVALUATION / ANALYSIS

- Site Investigations
- Foundation Characterization/Model
- Engineering Evaluations and Analyses
- Foundation Design
- Construction-phase Engineering
- Monitoring

4.1 Foundation Sliding Stability

- Identification of Critical Blocks
- Estimation of Shear Strength of Material
  – Discontinuities
  – Intact Rock
- Estimation of Uplift Pressures
- External Loads (Dam, Reservoir, Etc.)
- Analytical Methods

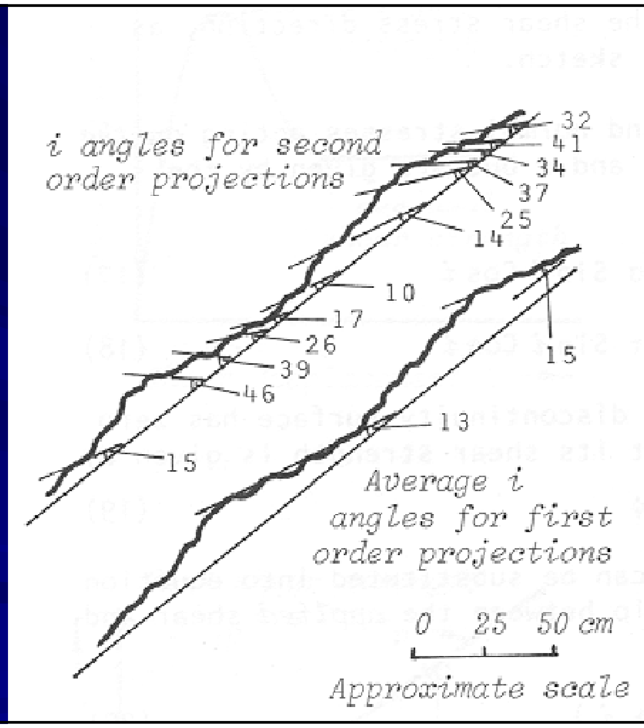




Morrow Point Dam: geologic mapping of the left abutment by geologist rappelling off top of abutment

Discontinuity Shear Strength Evaluation

- Basic or Fundamental Friction Angle
- Macro-Roughness or Waviness of Discontinuity
- Micro-Roughness
- Type and Characteristics of Infilling



4.2 Deformation

- Geological Model of Foundation Materials
- Estimation of Imposed Loads
- Estimation of Modulus of Deformation
- Use of Appropriate Analytical Models/Analysis Techniques

- *In-situ* Measurements
  – Borehole Dilatometer/Pressuremeter
  – Plate Jack Testing
  – Seismic Tomography
- Empirical Estimates
  – Lab Samples
  – RQD
  – Rock Mass Rating (RMR)
  – Geological Strength Index (GSI)

4.3 Seepage Analyses

- Model Configuration
  – Loads
  – Geologic Conditions/Anomalies
- Estimation of Material Properties
  – Hydraulic Conductivity
- Only an Estimation!

Estimation of Hydraulic Conductivity

- *In situ* Testing Methods
- How measured values vary over space and time under applied loads and seepage forces
- Analytical Methods
  - Crude flow nets
  - Sophisticated finite element models

4.4 Other Piping Issues

- High exit gradients combined with weak rock zones near downstream toe
- Method Proposed by Scott (USBR)
  - Determination of critical exit gradient
  - Determination of exit gradient under reservoir conditions
  - Comparison of gradients and determination of required foundation treatment.

4.5 Other Spillway Erosion / Overtopping Issues

- Simplified Approach
  - Relates stream power to erodibility index
  - Erodibility index is a function of:
    - Rock strength
    - Block size
    - Interblock strength
    - Block shape and orientation
- Rigorous Approach
  - Discrete element method (USCOE)
  - Keyblock (Reclamation)

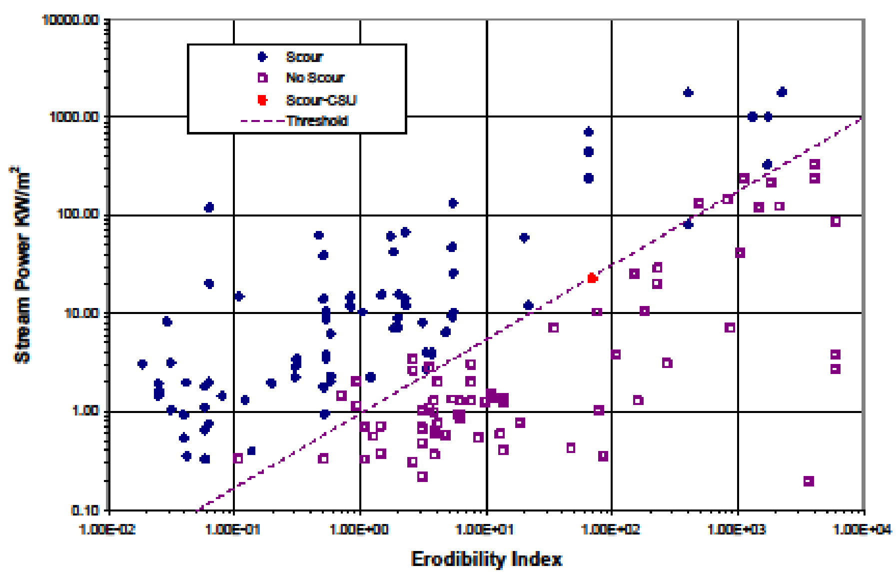


Figure 6 Erosion threshold relating stream power and the Erodibility Index (Annandale 1995; 2006)

5. FOUNDATION SURFACE PREPARATION

5.1 Excavation

5.2 Surface Preparation

5.1 Excavation

- Remove erodible, weak, compressible or pervious materials
- Repair defects in foundation such as faults, shears, or solutioned rock
- Reshape by removing or adding material
- Defend against erosion
- Bond between dam and foundation materials
- Fully understand the significance of all geologic features

- Design Intent – To provide suitable bearing at the least cost.
- Establishment of Excavation Criteria
  - Uniformly varying profile free of sharp offsets
  - Horizontal (upstream/downstream)

5.2 Foundation Surface Preparation

- Preparation of a foundation for a dam includes excavating, cleaning, treating, geologic mapping, and understanding before covering the foundation with concrete.

- Entire dam footprint should be cleaned to bedrock and unsuitable material removed. If blasting is required, smooth wall methods should be used to minimize damage to the foundation

- Remove all loose, drummy, and compressible material by
  - Air/water jet, barring, picking, brooming or vacuuming
- Remove all water by vacuuming, blotting, or air jet
- Should be clean enough to eat from

- Poor cleanup can reduce the compressive and shear strength, and the permeability at the contact, forming a weak zone
- Foundations with weak rock can be cleaned by placing a steel plate across the teeth of a backhoe and “shaving” or “peeling” objectionable material from the surface, minimizing hand cleaning

Slake Susceptible Rock

- Shale, siltstone, chalk, or mudstone may require protection against air and water slaking and freezing
- May leave final excavation until just before placement
- May immediately cover with 4 inches (minimum) of concrete
- Use a method of protection that prevents damage

Shaping

- The overall shape of the foundation should be smooth and not promote uneven stress distribution and cracking
- ALL overhangs should be removed
- Shape by:
  - Trimming
  - Smooth blasting
  - Dental concrete

Specialized Treatment

- Dental Concrete for Localized Areas
- Shear/Fault Zones
- Slake-prone Materials (Shales, Claystones)
- Karst

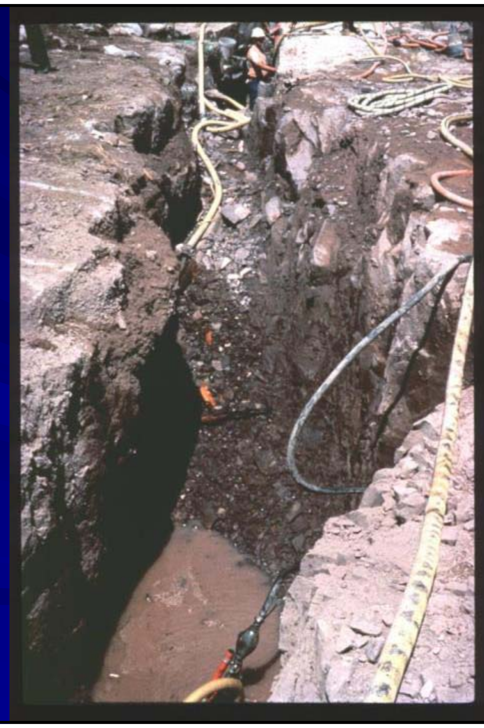
Dental Treatment

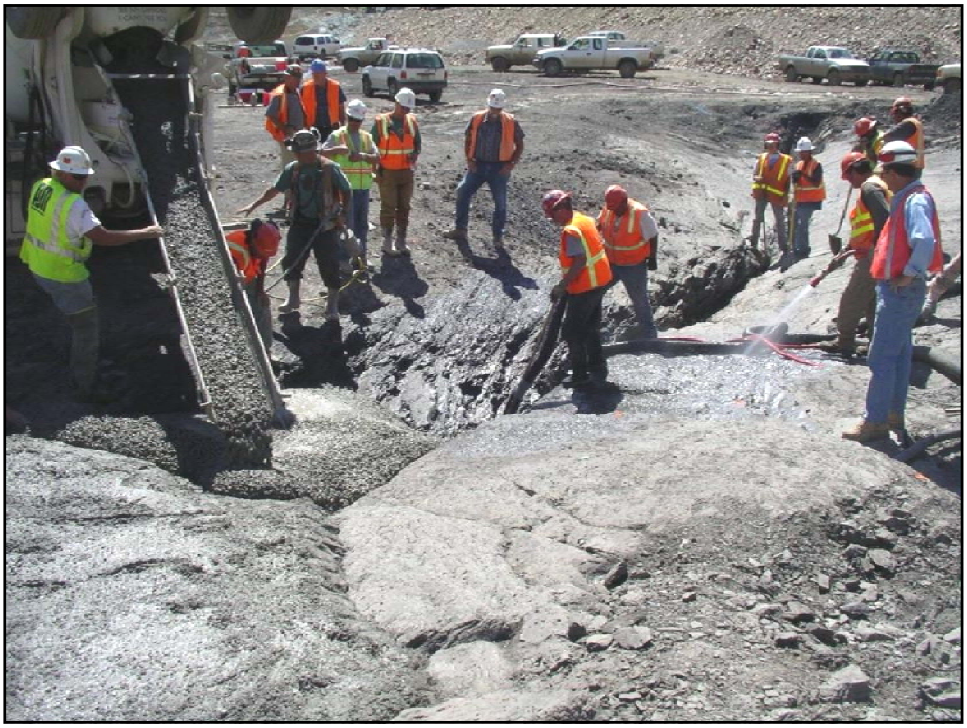
- Faults, shears, seams, or shattered or inferior rock are treated by removing the weak material and replacing with dental concrete.

- Dental concrete is the same material as backfill concrete, but used for shaping the surface more than filling larger zones below foundation grade, the difference is a matter of scale.

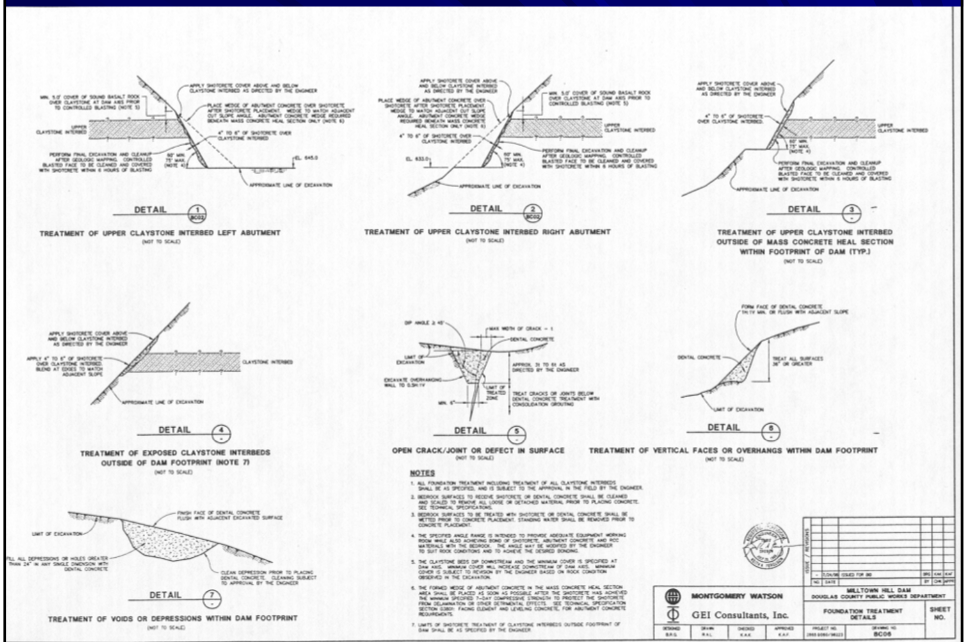
Upper Stillwater Dam

Shear zone being cleaned out for concrete backfill






02/19/2010



"General" Rule for Excavation Depth of Faults and Shear Zones

d = 0.002 bH + 5 [for H > 150 feet]

d = 0.3 b + 5 [for H < 150 feet]

where:

H = height of dam above general foundation level in feet,

b = width of weak zone in feet, and

d = depth of excavation of weak zone below surface of adjoining sound rock in feet. (In clay gouge seams, d should not be less than 0.1 H.)

FINAL DECISIONS MUST BE MADE IN THE FIELD DURING EXCAVATION OPERATIONS!!

"General" Rule of Thumb for Treatment of Small Features

- Openings narrower than 2 inches should be cleaned to a depth of three times the width of the opening
- Openings wider than 2 inches and narrower than 5 feet should be cleaned to a depth of three times the width of the opening or to a depth where the opening is 1 inch wide or less

6. FOUNDATION TREATMENT AND DRAINAGE

6.1 Background

6.2 Contemporary Grouting Practices

6.3 Drainage Curtains

6.1 Background

- Seepage Reduction through Foundation
- Reduction of Uplift Pressures on Gravity Dams
- Minimize flow paths and erosive velocities at soil to rock interface of embankment dams
- Reduce settlement and potential cracking of concrete dams
- Contraction Joint Grouting post shrinkage
- An element of a "Composite Cutoff" wall

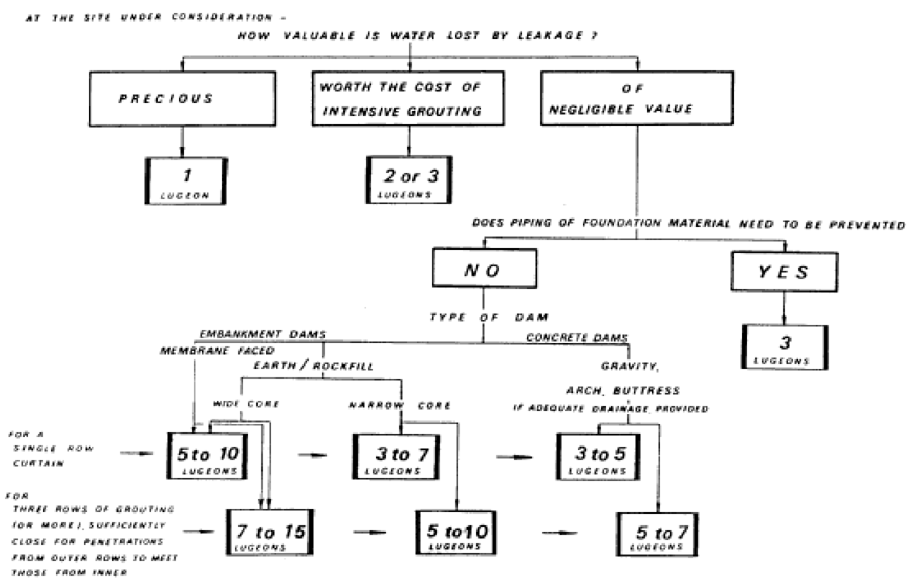
Common Denominator of Typical Applications

- All involve filling of rock joints or defects to:
  - Reduce Rock Mass Permeability to reduce seepage volume
  - Improve rock mass strength
  - Reduce potential settlement or subsidence

Grouted Cutoffs for Seepage Reduction

- Grouted Cutoffs are commonly referred to as "Grout Curtains"
- Term Grout Curtain is a misnomer
  - Infers a thin continuous element (e.g. shower curtain or membrane)
  - In reality, grouted zone width is highly variable. Wider grouted zone in open joints, thinner zone in joints of moderate opening, and very limited width in very tight joints or fine fractures.
  - Curtains may contain defects due to missed joints or bleed water accumulation

When is Grouting Necessary?



From: Houlsby 1990

Figure 8.3-3A. Guide to the need for grouting of a dam.

Curtain Grouting

- Grouting Objectives
- Single Row Curtain
- Multiple Row Curtain
- Typical Hole and Line Spacing

Grouting Objectives

- Reasons for Grouting:

  1) Reduce permeability and seepage

  2) Minimize uplift pressures on structure

  3) Not grouting the rock. Grouting defects or discontinuities

Grouting Lingo

- Primary Hole – First Hole Series
- Secondary Hole – Second Hole Series
- Tertiary Hole – Third Hole Series
- Quaternary Hole – Fourth Hole Series
- Quinary Hole – Fifth Hole Series

etc., etc., etc……

Closure Grouting

Step 1: Drill and grout primary holes.

Step 2: Split space primary holes with secondary holes.

Step 3: Split space primary and secondary holes with tertiary holes.

Step 4: Continue with additional holes series as necessary to achieve desired results.

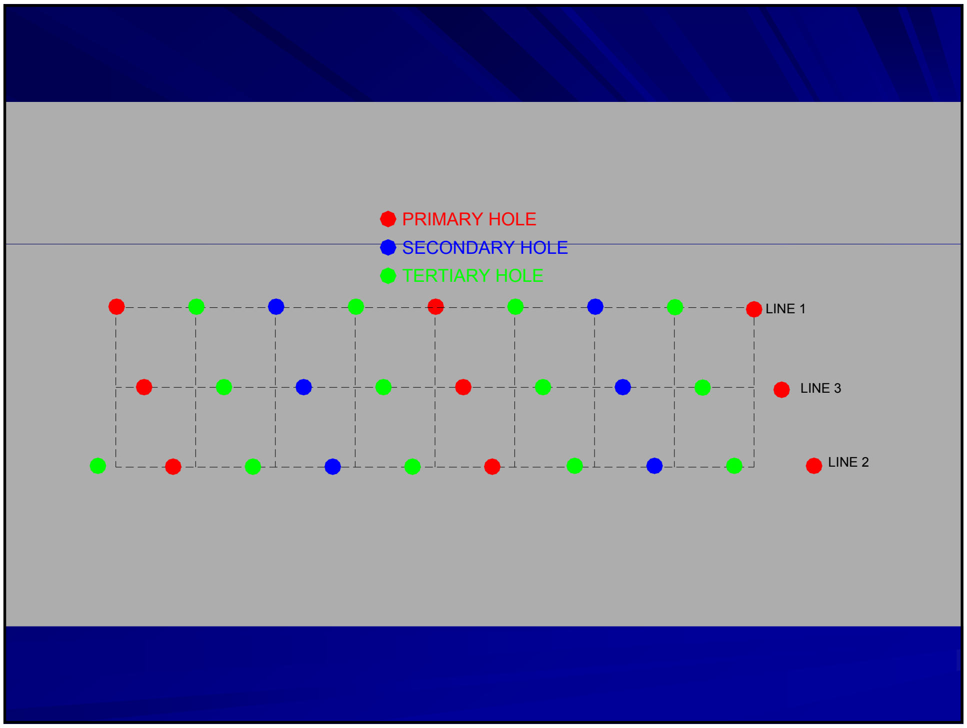
Single Row Curtain

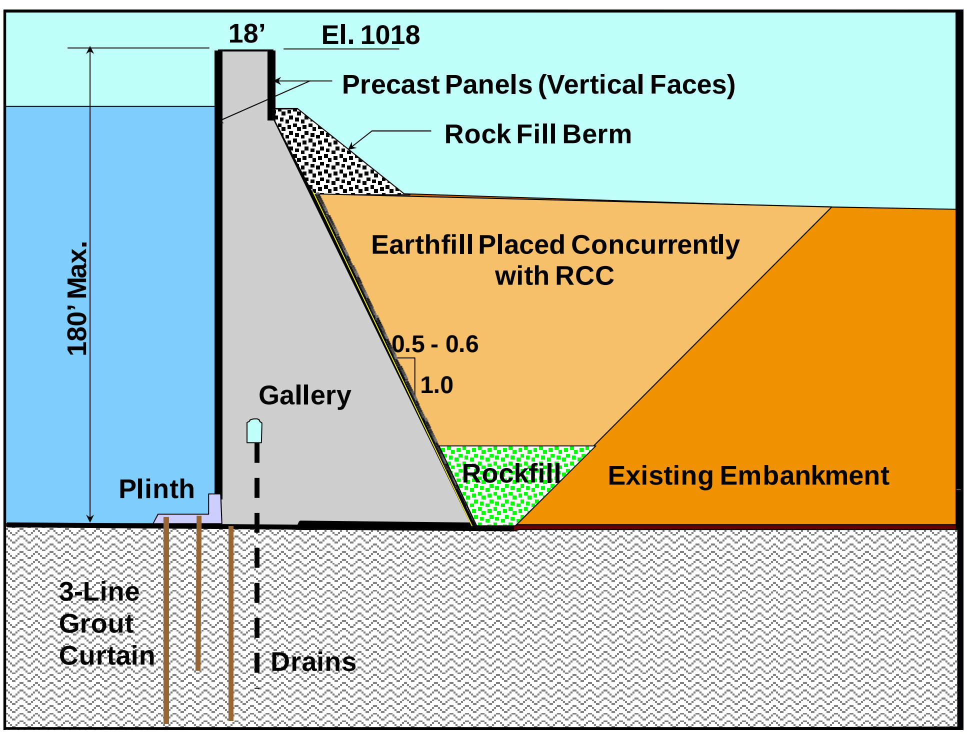
- Applicable only to sites with excellent rock quality and rock durability.
- Penetration of grout in fine fractures must be considered, i.e. width of curtain.
- Requires good grouting techniques and thorough analysis of results.
- Some zones may require additional holes offset from single line.

Single Row Curtain

Multiple Row Curtain

- Provides thicker zone of improved foundation (wider curtain).
- Lesser chance of defect not being intersected and treated.
- Verifiable results with closure line.
- Essential where erodible material exists.


PRIMARY HOLE
SECONDARY HOLE
TERTIARY HOLE
LINE 1
LINE 3
LINE 2


18'
El. 1018
Precast Panels (Vertical Faces)
Rock Fill Berm
180' Max.
Earthfill Placed Concurrently with RCC
0.5 - 0.6
1.0
Gallery
Rockfill
Existing Embankment
Plinth
3-Line Grout Curtain
Drains

Grout Hole Spacing

- Typical Primary hole spacing of 20 to 40 feet (6 to 12 meters).
  - Typical spacing selected to minimize connections during grouting of primary holes
- Spacing is highly dependent upon geology and required frequency of grout hole intersections with formation joints.
- Err on the side of caution when determining hole spacing and required number of holes.
- Final hole spacing is typically 5 to 10 feet (2 to 3 meters)

Grout Hole Inclination

- Grout hole inclinations should be designed to intersect open joints as frequently as possible.
- Designers must have thorough understanding of site geology.
- Equipment limitations also must be considered.

Grout Hole Spacing

- Houlsby, “It is important to make the spacing between rows in multiple curtains a distance that is less that about twice the general penetration distance.”

- Therefore, fine fractures with short grout penetration distance equals tightly spaced rows. Large fractures with long grout penetration distance equals wider row spacing.

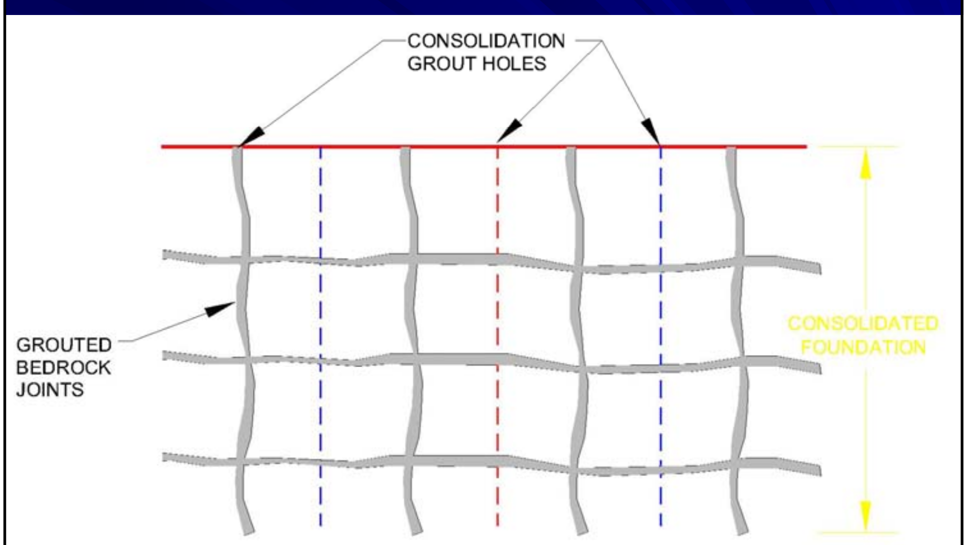
“Consolidation” Grouting

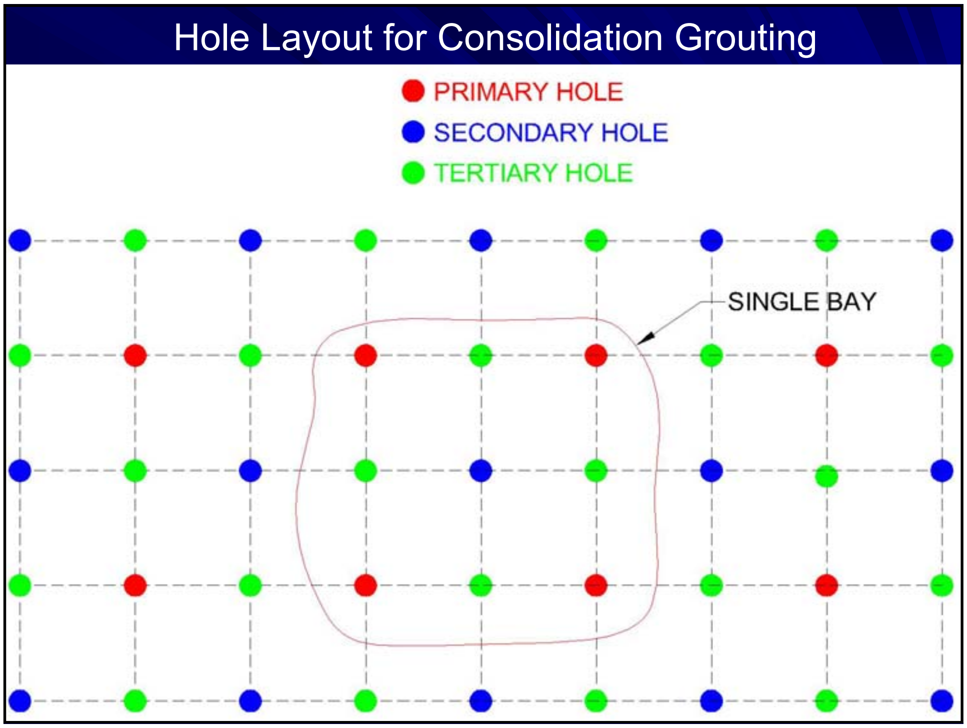
a.k.a. Blanket Grouting

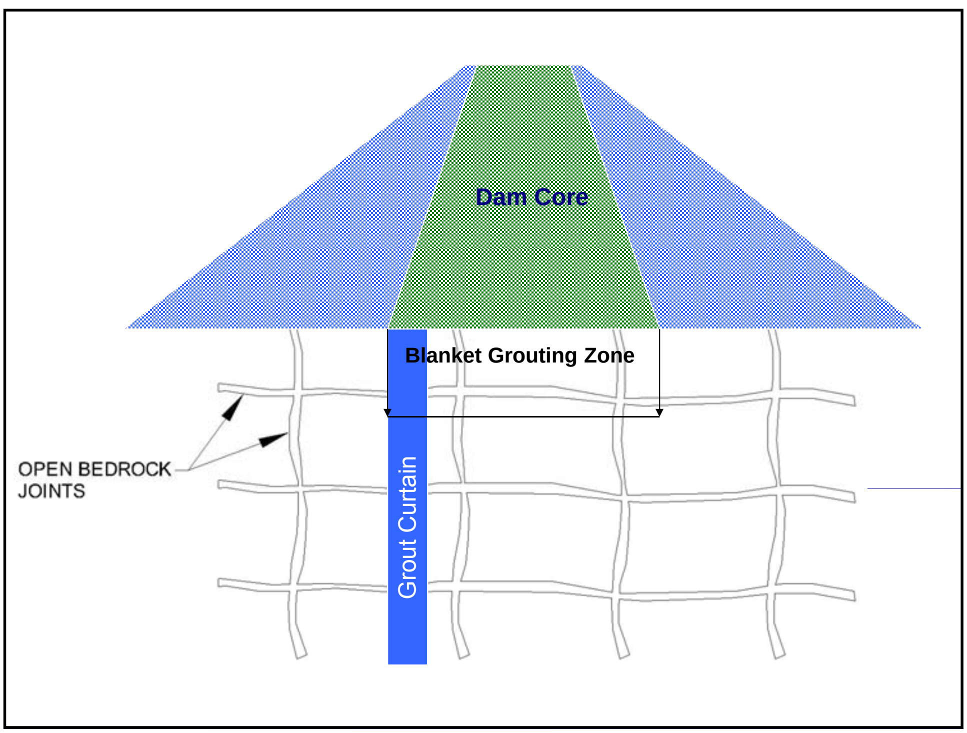
- When is it necessary?
  - USBR Rule of Thumb – Consolidation grouting performed for gravity dams 100’ or higher
- Consequences if not utilized
- Typical layouts
- Typical hole spacing
- Typically ≤ 30-foot depth

Reasons for Blanket Grouting

- Whenever structural movements must be minimized
- Minimize potential for erosion at soil rock interface within core contact area
- Treatment of weathered zones at depth (cheaper than excavation and backfill)
- Reduction in foundation permeability




Hole Layout for Consolidation Grouting
PRIMARY HOLE
SECONDARY HOLE
TERTIARY HOLE
SINGLE BAY


Dam Core
Blanket Grouting Zone
OPEN BEDROCK JOINTS
Grout Curtain

Blanket Grouting Hole Spacing

- Primary hole spacing typically 40 feet (12 meters), and final hole spacing not more than 5 feet (1.5 meters).

- Poor rock quality and frequent grout connections to adjacent holes may necessitate wide primary hole spacing.

Grout Caps

- Why should they always be considered or used?
  - Higher pressures can be used on top stage
  - Eliminates the need for grout nipples (packer can be set within the grout cap
  - Regularizes the foundation surface
    - Aids accessing hole locations
    - Reduces potential for hole contamination
  - Increases worker safety and productivity
    - Cleaner working environment – reduces tripping or slipping hazards
    - Can be constructed to drain to facilitate site cleanup

Before

After

General Rules Regarding Grout Caps

- Cutoff walls or concrete grout caps should not be blasted!
- Blasting for the excavation of these structures should be prohibited or strictly controlled to avoid damaging the foundation.
- Grout caps are always beneficial.

6.2 Contemporary Grouting Practices

- "Traditional" 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).

- “Traditional” 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:

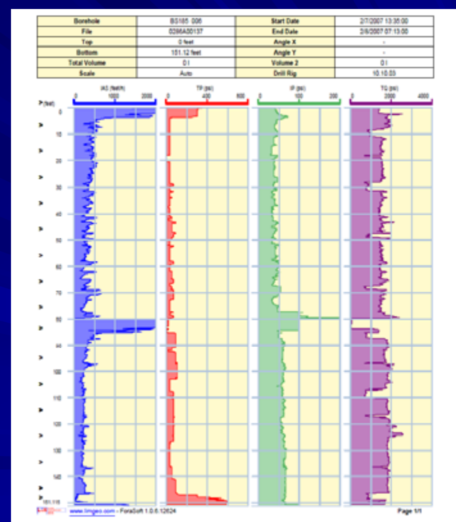
> "*In preparing this paper, I requested copies of current specifications for foundation grouting from several Corps of Engineers districts, the TVA and Bureau of Reclamation. In comparing these current specifications with copies of specifications that I had in my files that are 30 years old, plus my 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.

- 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.

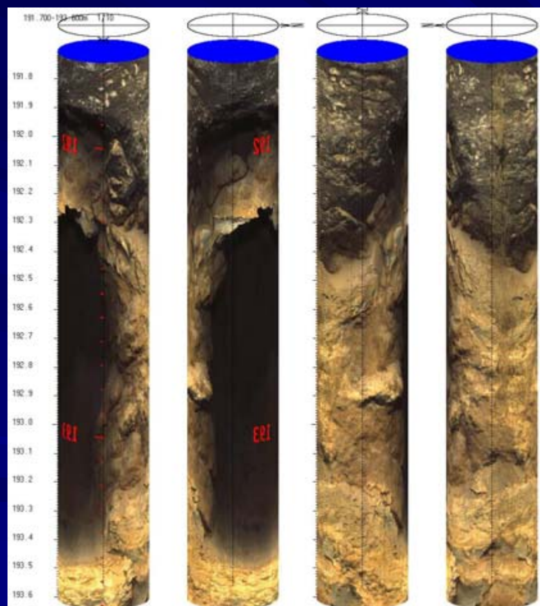
– Notes:
  1. The associated design improvements included:
     - multirow curtains;
     - inclined holes in each row;
     - depth of curtain determined by geology and/or by rigorous seepage analyses;
     - stage lengths commensurate with the structural geology;
     - use of the highest safe grouting 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).

Monitoring While Drilling (MWD)



High Resolution Borehole Imaging



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

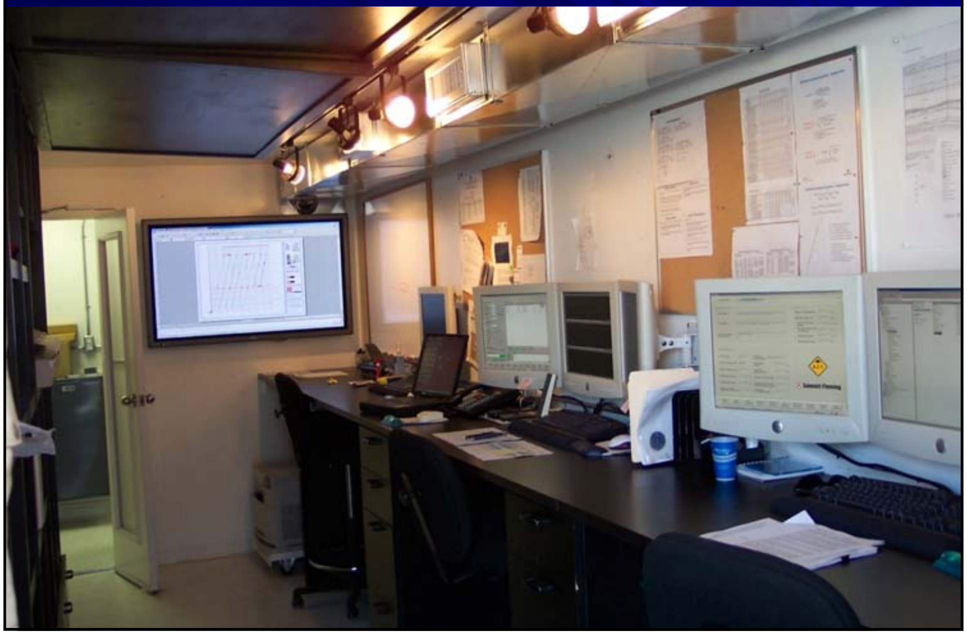
Wrapped image
suggests feature trends
NW-SE, normal to dam.

- 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.)

Monitoring Equipment

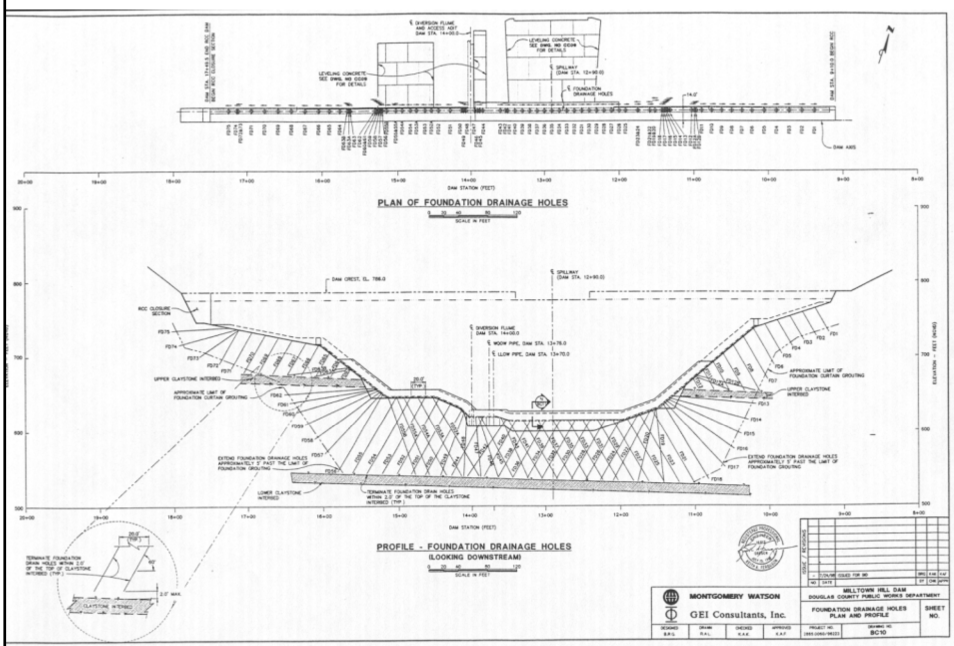
- Computer Control and Analysis
  - First CAGES (ECO Grouting), soon modified to “Intelligrout,” to record, analyze, control and display all injection parameters in real time.
  - Use of Apparent Lugeon Theory (Naudts) predicated on development of stable mixes.
- Verification
  - Use of “Intelligrout”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

Level 3 Computer Monitoring System



6.3 Drainage Curtains

- Positive solution to reduce uplift pressures
- Objectives
  - Reduce uplift pressures and enhance stability
  - Provide safe collection and discharge of seepage



- Most effective when located as far upstream as possible without jeopardizing the seepage reduction features (grouting, etc.).
- Must be accessible for observation and maintenance

7. FINAL REMARK

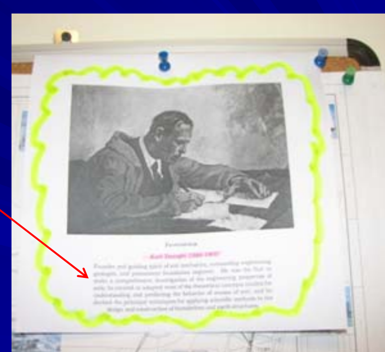
"To pass judgment on the quality of a dam foundation is one of the most difficult and responsible tasks. It requires both careful consideration of the geological conditions and the capacity for evaluating the hydraulic importance of the geological facts . . . "

Karl Terzaghi, 1929

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 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."

REFERENCES

- Engineering Geology Field Manual, USBR
- Geotechnical Studies for Concrete Dams, USBR
- Dam Foundation Engineering, 10th Annual Meeting, US Society on Dams, New Orleans, 1990.
- Rock Foundations for Dams, ICOLD Bulletin 88, 1993.
- "Geologic Factors Influencing Dam Foundation Failure Modes," Doug Boyer, 2006 USSD Annual Meeting.
- "Engineering Geology Considerations for Specifying Dam Foundation Objectives", Bill Fraser, CA Division of Safety of Dams, 2001.
- Grouting Manual EM-1100-2-3506, USACE, July 31, 2014.

ACKNOWLEDGMENTS

Doug Boyer

Geo-Institute

Ken Hansen

Tom Fitzgerald

Gary Rogers