Alternative Measures (for Cutoffs) for Dams on Karst

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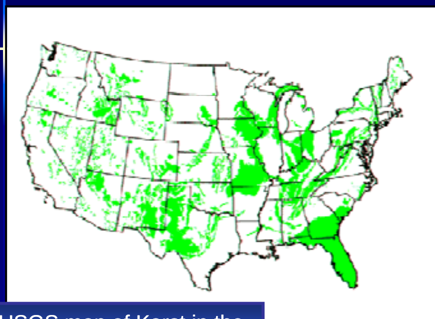
Agenda

1. Introduction and Background
   - Failure Modes
   - Three Techniques
     i. Category I Walls (Excavate/Replace)
     ii. Grouting and "Composite Walls"
     iii. Category II Walls (Mix-in-Place)
2. Category I Walls (Excavate/Replace)
3. Grouting and "Composite Walls"
4. Category II Walls (Mix-in-Place)
5. Final Remarks

1. Introduction and Background



USGS map of Karst in the US.

Center Hill Dam, TN – 1983 Muddy Show

Clearwater Dam, MO – Sinkhole January 15, 2003

Large number of major dam safety incidents involving complex seepage/piping failure mode development processes

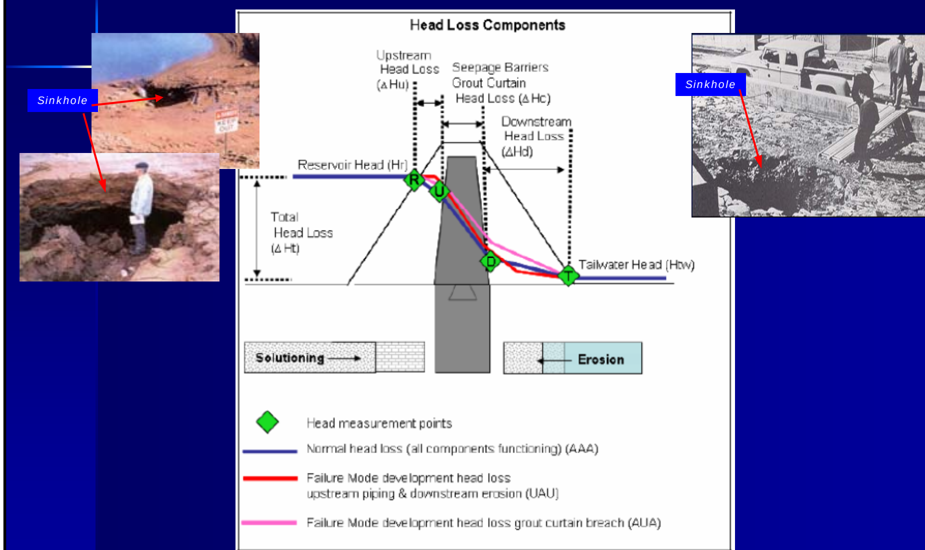
Large number of other dams in similar environments with similar design and construction provisions

Typical Well-Known Examples

Name of Dam	Date(s) of Incidents	Comments
Wolf Creek Dam, KY	**1960's**	**Increasing seepage, sinkholes along downstream toe of dam, muddy show**
Center Hill Dam, TN	**1969 - 1983**	**Increasing seepage, sinkholes along downstream toe of dam, muddy show.**
Quail Creek Dam, UT	**1980's**	**Increasing seepage, toe drain failure, dam failure.**
Mosul Dam, Iraq	**1970's to present**	**Sinkholes along downstream toe, abutments and increasing seepage**
Clearwater Dam, MO	**Jan 2003**	**Increasing seepage, sinkhole on Upstream face of dam.**
Horsetooth Dam, CO	**Early 2000's**	**Sinkholes along upstream toe of dam and increasing seepage**
Arapuni Dam, NZ	**1927 to 1995**	**Increasing seepage**

Numerous other case histories exist

Failure Modes



Erosion Failure Modes

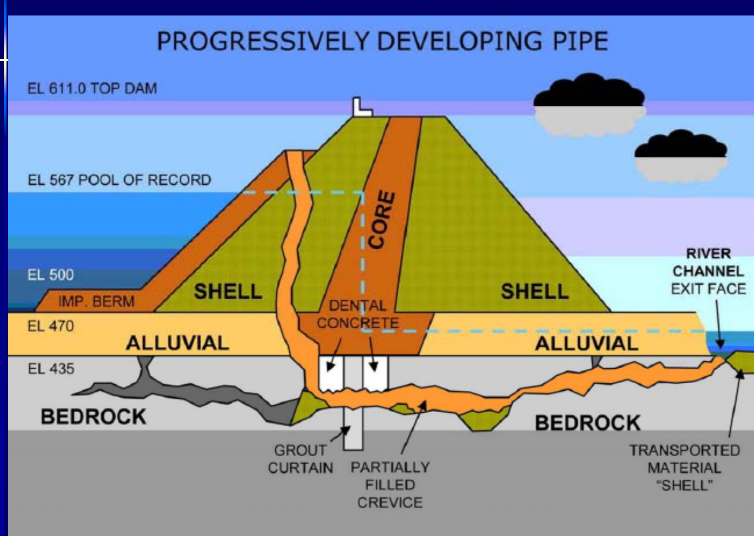


Figure courtesy of USACE

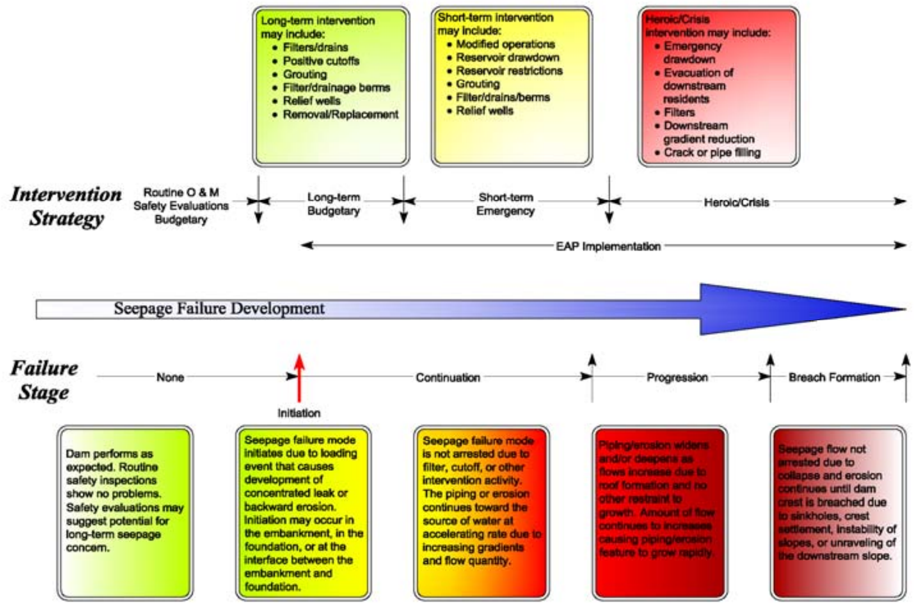
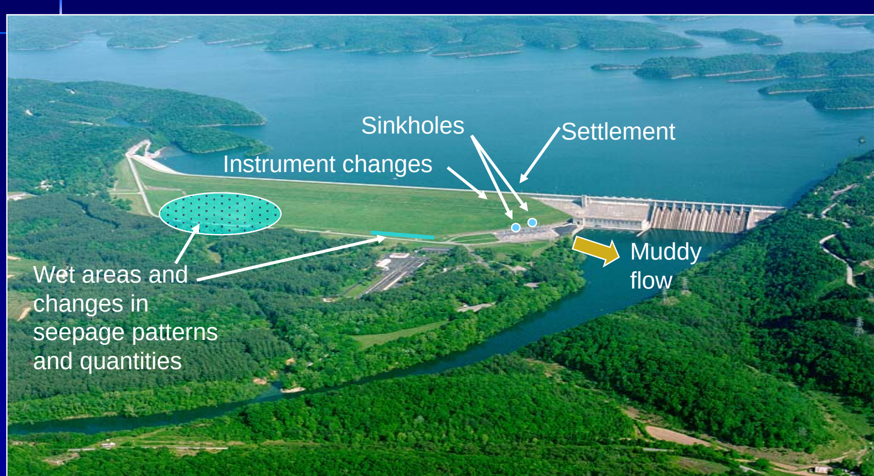


Figure 5
Seepage / Piping Failure Continuum

Distress Indicators for Existing Dams



Geologic Characteristics of Karst, Erodible and Soluble Foundations

Structural Controlled Karst with connection to base of dam

Stratagraphically controlled Karst with no connection to base of dam

Clay Filling

Open flowing 20 to 30 gpm under low head

Design Features Leading to Development of Safety Incidents/Failures

– Inadequate treatment of foundation defects
– Incomplete or inadequate grout curtains and/or cutoffs
– Inadequate embankment filter/drainage provisions

Caves along cutoff trench – Wolf Creek Dam

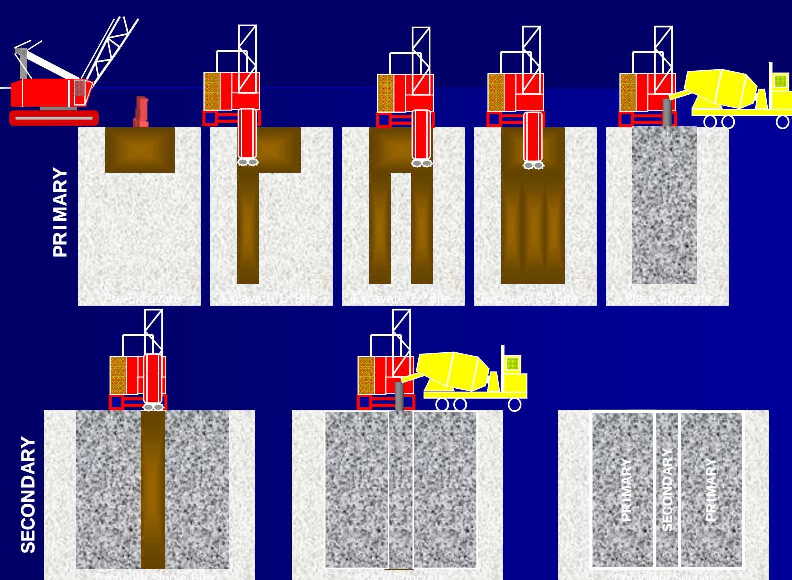
Key Factors in Assessing Risk Profile

Left Abutment Sinkhole – Center Hill Dam

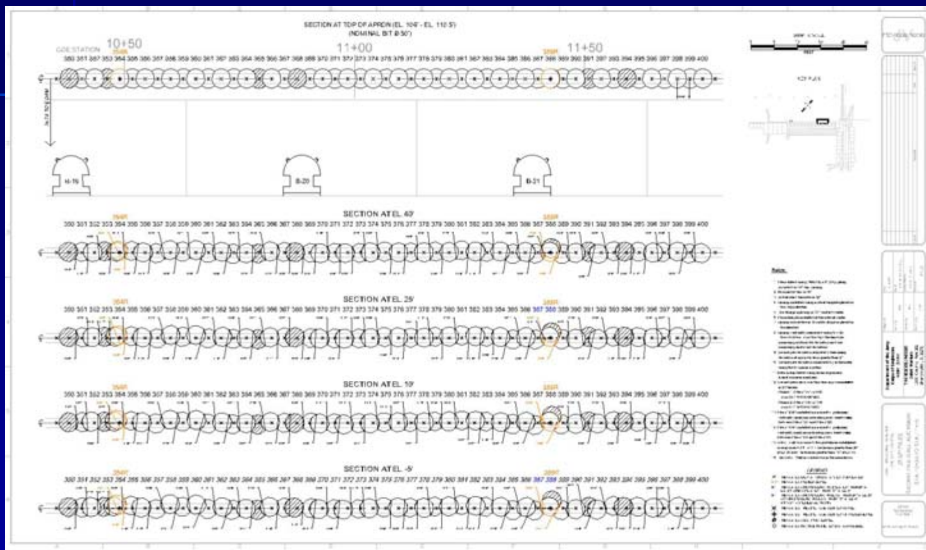
- Site geology
- Design Features
  - Depth of foundation treatment
  - Interface treatment
  - Embankment provisions
- Depth of reservoir
- Time since first filling
- Erodibility of Karst or open joint infilling materials
- Solubility and reservoir water chemistry

All these factors must be considered when assessing the risk profile and potential risk of future failure mode development. Current performance may not be an indicator of future safety. Solution and erosion processes are dynamic.

2. Concrete Cut-Off Walls (Category I) Using the Panel Method



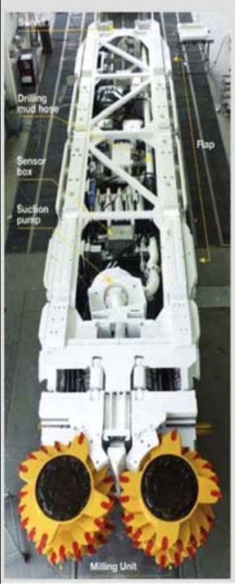
Concrete Cut-Off Walls Using Secant Piles



Clamshells
(Cable or Hydraulic)

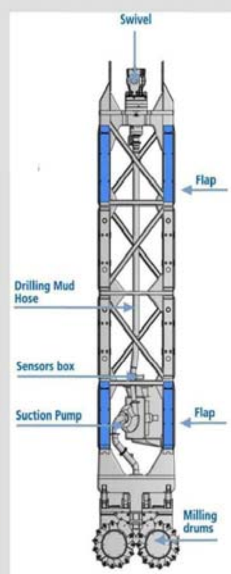
Hydromill (Cutter)

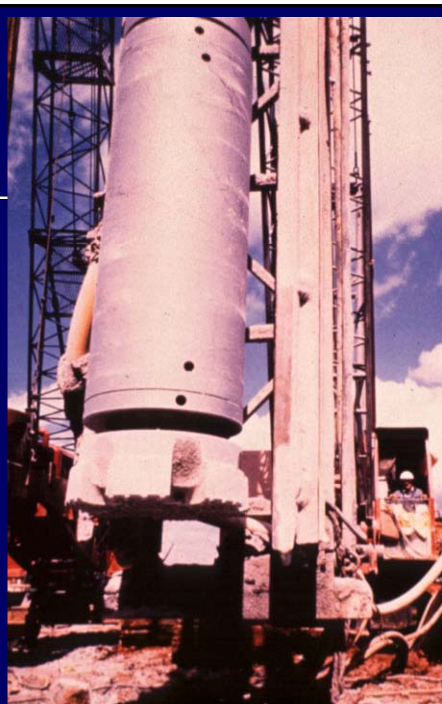
HYDROMILL TECHNOLOGY



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.





Conventional Secant Pile Method

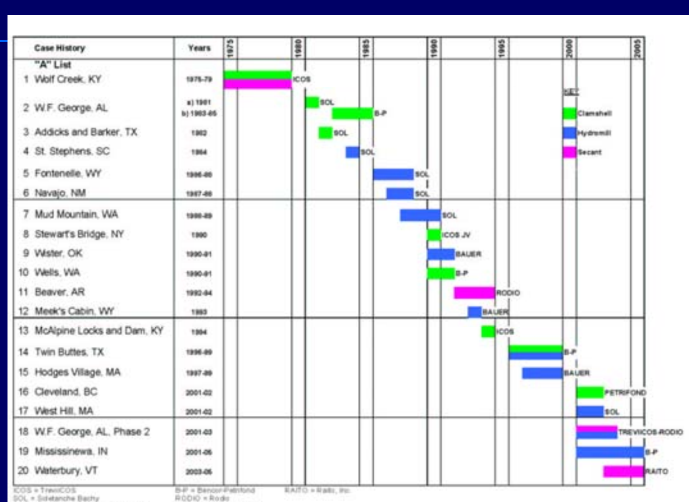

W.F. George, AL

U.S. Case Histories to Date

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project: Area	Min. Width	Depth	Length	References
1. WOLF CREEK, KY. 1975-1979	ICOS	24-inch diameter Primary Piles, joined by 24-inch wide clamshell panels. Two phases of work.	Concrete.	Dam FILL, and ALLUVIUM over argillaceous and karstic LIMESTONE with cavities, often clay-filled.	To provide a "Positive concrete cut-off" through dam and into bedrock to stop seepage, progressively developing in the karst.	270,000 sf (Phase 1) plus 261,000 sf (Phase 2)	24 in	Max. 280 ft	2,000 ft plus 1,250 ft	• ICOS brochures (undated) • Fetzer (1988)
2. W.F. GEORGE, AL 1981 1983-1985	Soletanche (Phase 1) Bencor-Petrifond (Phase 2)	26-inch thick panels using cable and kelly-mounted clamshell 24-inch panels 15-27 ft long	Plastic concrete 3,000 psi Concrete	Random, impervious FILL with silty core over 25-30 ft ALLUVIUM over chalky LIMESTONE	To provide a "positive concrete cut-off" through the dam and alluvials.	130,000 sf (Phase 1) plus 951,000 sf (Phase 2)	26 in 24 in	Max 138 ft 110-190 ft	Approx. 1,000 ft 8,000 ft	• Soletanche Brochure (undated) • Bencor Brochure (undated)
3. ADDICKS AND BARKER, TX. Completed in 1982 (Phase 1 took 5 months)	Soletanche*	36-inch thick panel wall with clamshell excavation using Kelly.	Soil-Bentonite.	Dam FILL over CLAY.	To prevent seepage and piping through core.	450,000 sf (Phase 1) plus 730,000 sf (Phase 2)	36 in	Max 66 ft typically 35 to 52 ft	8,330 ft plus 12,900 ft	• Soletanche website.
4. ST. STEPHENS, SC. 1984	Soletanche	24-inch-thick concrete panel wall, installed by Hydromill. Plus upstream joint protection by soil-bentonite panels.	Concrete and soil-bentonite.	Dam FILL, over sandy marly SHALE.	To provide a cut-off through dam.	78,600 sf (concrete) plus 28,000 sf (soil-bentonite)	24 in	Max. 120 ft including 3 ft into shale	695 ft	• USACE Report (1984) • Soletanche (various) • Parkinson (1986) • Bruce et al. (1989)

* Soletanche have operated in the U.S. under different business identities over the years. "Soletanche" is used herein as the general term.

Project Listing Showing Chronology Type of Cut-Off and Specialty Contractor (1975-2007)



Concrete Cut-Offs for Existing Embankment Dams

Type of Construction	Number of Projects	Square Footage		
		Smallest	Largest	Total
Mainly Clamshell	7	51,000	1,400,000	3,986,320
Mainly Hydromill	9	104,600	850,000	2,389,415
Mainly Secant Piles	4	12,000	531,000	1,050,700
Total	**20**			**7,426,435**

2006-2013 Update

Dam	State	Scope	Status of Project as of Fall 2013
Wolf Creek	KY	Approximately $400M Category 1 cutoff to 275′ depth.	Complete.
Clearwater	MO	Approximately $100M Category 1 cutoff to 150′ depth.	Complete.
Center Hill	TN	Approximately $110M Category 1 cutoff to 300′ depth.	30% complete.
Herbert Hoover Dike	FL	About 22 miles of Category 1 and 2 cutoff to 90′ depth.	Complete.

In addition, major cutoff walls are in design stage for other USACE DSAC 1 and 2 dams including East Branch, Bolivar, Mohawk and Addicks & Barker Dams.

3. Review of Contemporary Grout Curtain Technology: The Evolution of the Revolution

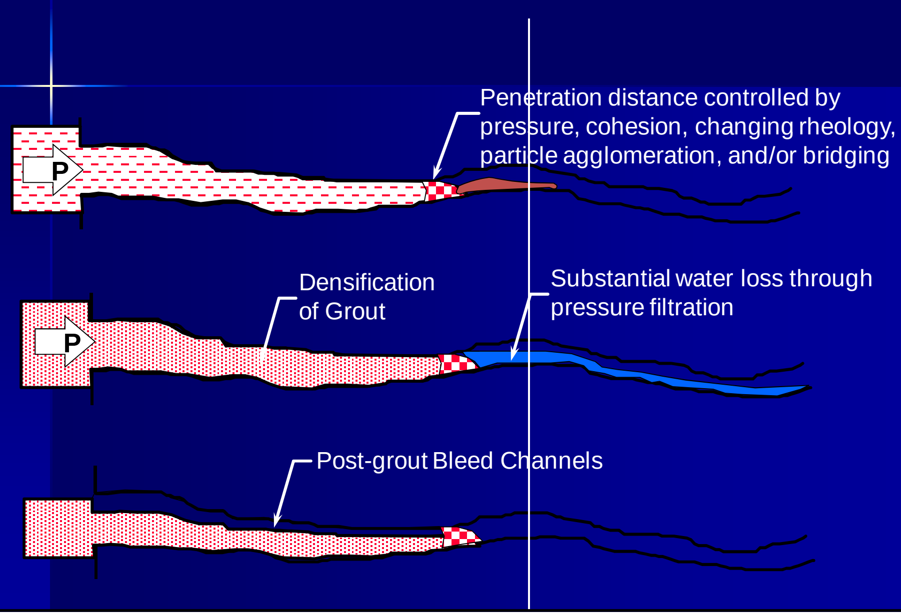
Revolutionary Elements 1996-Present

- Quantitative Design
  - Intensity of Grouting consistent with design, assumptions and requirements.
- Hole Orientation and Depth selected consistent with site geology.
- Stable Grouts with multiple admixtures.
- Pressures – Maximum safe pressure utilized.
- Data Acquisition – Flowmeters and Pressure Transducers.
- Data Recording – Computer Monitoring by experienced Engineer or Geologist.
- Note: talk focuses on cutoffs as opposed to blanket (“consolidation”) grouting. However, the same procedural principles apply.

Characteristics of Unstable Water Cement Grouts

- Cement + Water
- Considerable Bleed Potential
- Low Resistance to Pressure Filtration
- Unorganized Particles
- Unpredictable Behavior due to Changing Rheology During Injection
- Marginal Durability

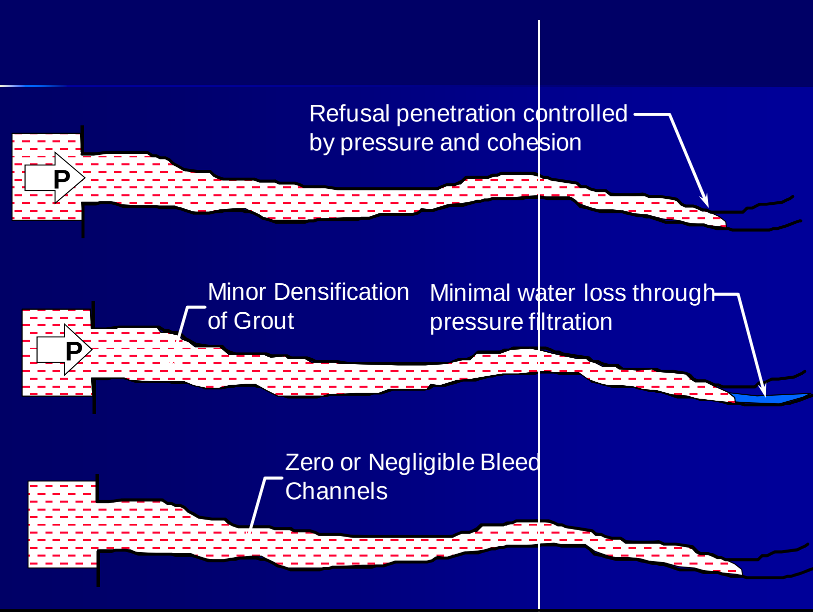
Grouting Theory - Neat Cement Grouts



Characteristics of Balanced Stable Water Cement Grouts

- Cement + Water + Rheology Modifiers
- Zero Bleed
- Resistant to Pressure Filtration
- Organized Particles
- Minimal Change in Rheology During Injection

Grouting Theory - Balanced, Stable Grouts



Common Additives to Balanced Stable Cement-Based Suspension Grouts

- Water
- Portland Cement (typically Type III)
- Bentonite
- Silica Fume
- Flyash (usually Type F)
- Welan Gum or other Viscosity Modifier
- Dispersant (SuperP)

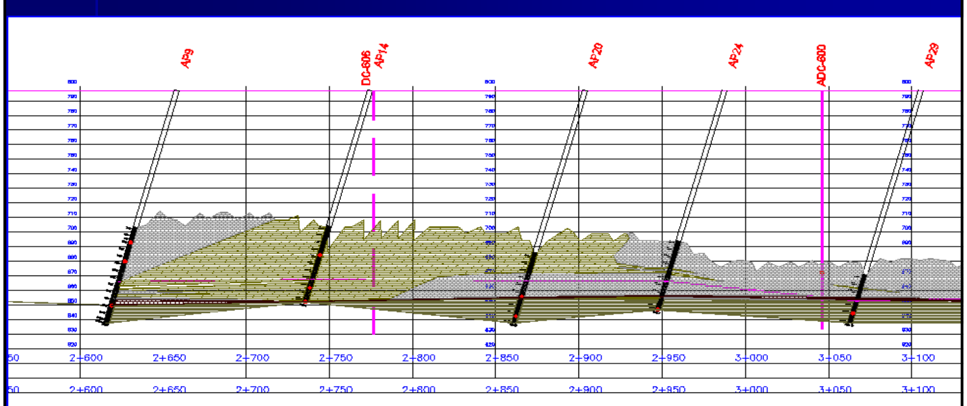
Level 3 Computer Monitoring System

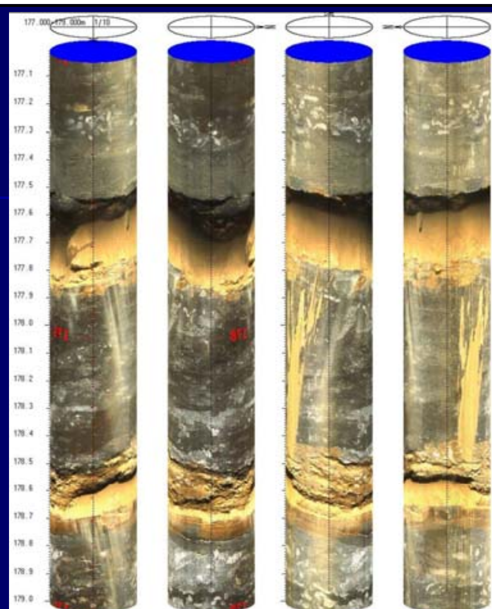
Advantage: Grouting

- Measurement Accuracy Significantly Improved
- Real Time Data is obtained (2-10 seconds vs. 5-15 min.)
- Allows one to use higher pressures with confidence;
- Dilation and Lifting easily picked up on screen
- Formation Responses to procedure changes (mix or pressure) are known immediately
- Accelerates the Work
- Reduces Inspection Manpower Requirements (~25% for Level 2 Technology and ~60% for Level 3)
- Permits reallocation of resources to analyze program results and recommend cost effective program modifications.

Advantages: Interactive Geology

- Logical organization of Geotechnical and Geological Data
- Electronic link between data
- Eliminates sorting through paper logs, photographs, lab test results, etc. to interpret conditions





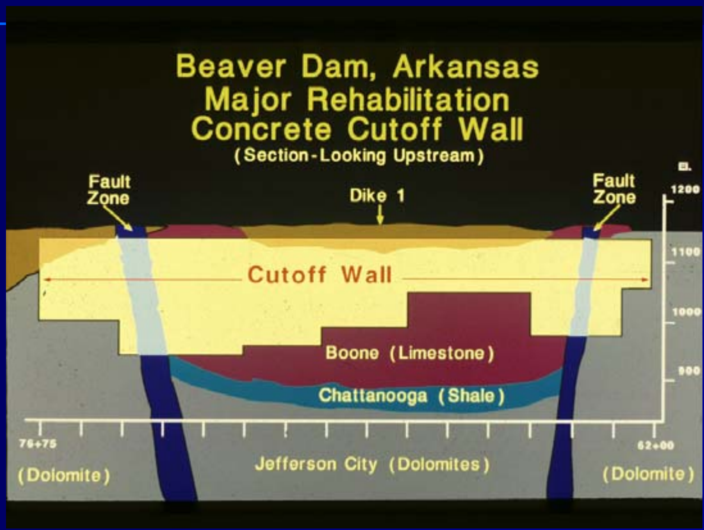
"Virtual Rock Core" Showing Weathered Partially Clay Filled Joints in Limestone Formation

"Composite" Cut-Off Solution for Carbonate Foundations

<u>Basic Principles</u>

- Modern grouting methodologies can be relied upon to provide durable, effective cut-offs, <u>provided</u> significant fine material (e.g., fine karstic detritus) is not retained in the grout/rock structure comprising the cut-off.

- Concrete cut-off walls are essential to provide durable, effective cut-offs through rock masses found to contain significant amounts of karstic material which can be eroded under service conditions.



- However, the price of a concrete cut-off wall can be up to 10 times that of an equivalent grout curtain and the huge equipment required may be incompatible with site logistics. Furthermore, most of the cut-off will be in rock of high strength and/or minimal clay presence: why excavate 20,000 psi rock to replace with 3,000 psi concrete?

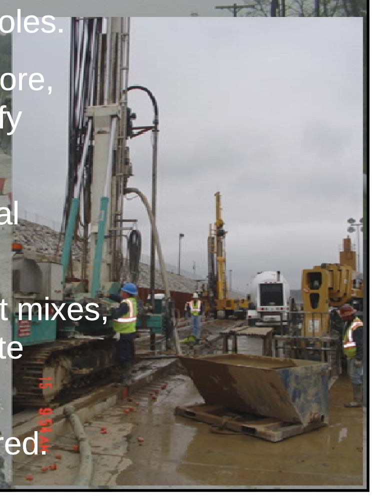
…and pay for the privilege!

Basic Premise

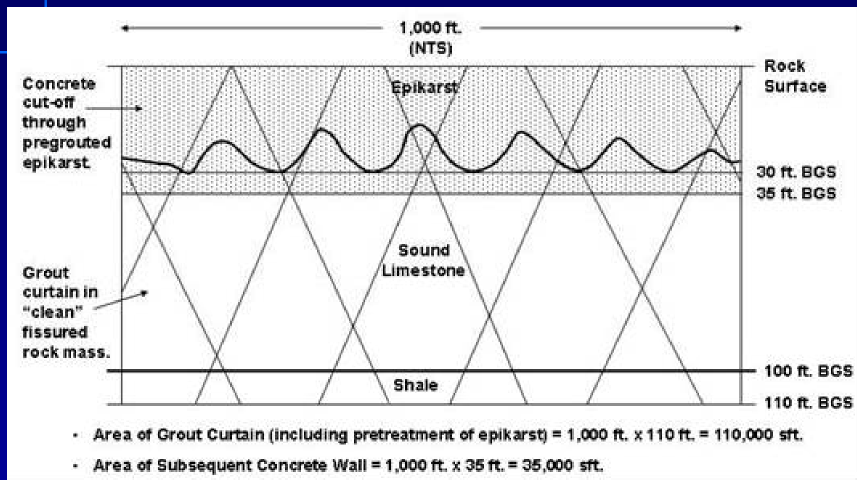
- Conduct high quality drilling and grouting operation along the whole alignment as the first, engineered step, not as an intermittent and/or emergency operation.
- This operation will:
  1. Provide a very high intensity of site investigation data upon which to optimize the depth and extent of the subsequent concrete cut-off wall.
  2. Pretreat the epikarst and other voided areas to prevent massive, sudden loss of bentonite slurry during the excavation for the concrete cut-off. (Potentially a dam safety issue.)
  3. Provide a cut-off in "clean" rock conditions, of an engineered residual permeability.
- Build cut-off wall <u>only</u> where required.

Highlights of a Drilling and Grouting Program for Composite Walls

- Minimum 2 rows of inclined holes, either side of the potential cut-off wall alignment.
- "Measurement While Drilling" all holes.
- Intense water pressure testing before, during and after grouting to quantify conditions.
- Use of Optical Televiewer in special features.
- Use of modified, stable HMG grout mixes, and LMG as appropriate. (Absolute refusal.)
- Build cut-off wall <u>only</u> where required.

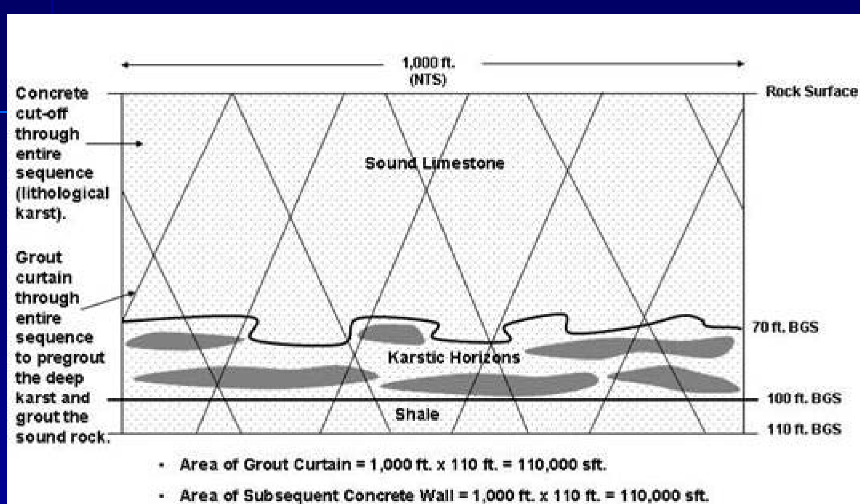


Illustrative Examples: “Clearwater” Case



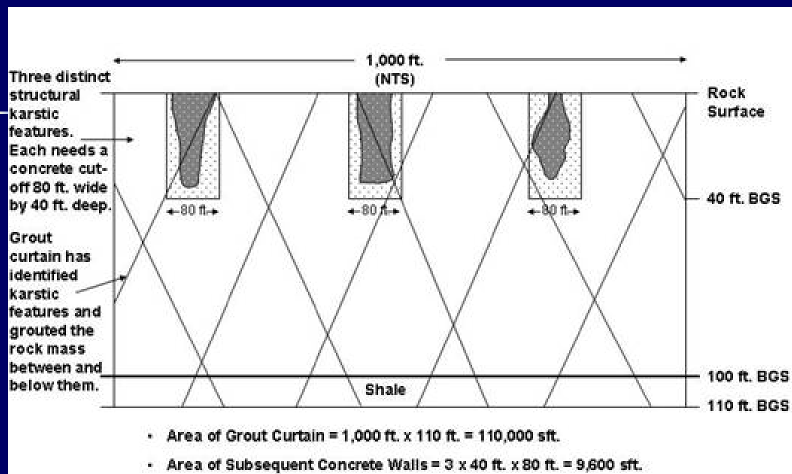
Epikarst is found during pregrouting to an average of 30 ft. b.g.s. The concrete cut-off needs only to be installed to 35 ft. b.g.s.

“Wolf Creek” Case



Heavily karstified horizons are found at depth. Therefore the concrete cut-off is required for the full extent. The grouting has pretreated the karstic horizons to permit safe concrete cut-off construction.

"Bear Creek" Case



Discrete karstic features have been found, structurally driven. Thus, individual concrete cut-offs can be installed, after drilling and grouting has confirmed the extent of these features and has pretreated them to permit safe concrete cut-off construction.

4. Category II Walls (Mix-in-Place)

Classification of Deep Mixing Methods as at 2008

- Rotary Vertical Axis
  - Wet End Mix
  - Wet Shaft Mix
  - Dry End Mix
- Jet Assisted Vertical Axis (Turbojet)

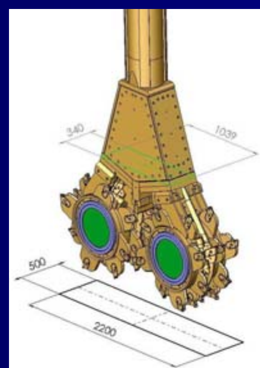
"Conventional"

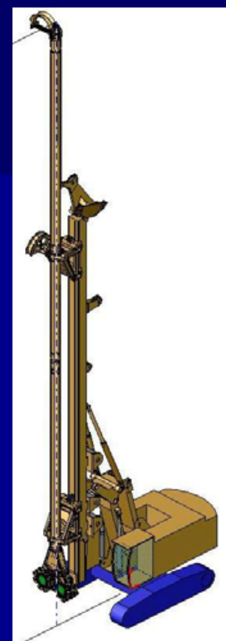
- Trench Cutting and Mixing (TRD)

- Horizontal Axis Cutting and Mixing
  - Low Pressure (CSM)
  - High Pressure (CT Jet)

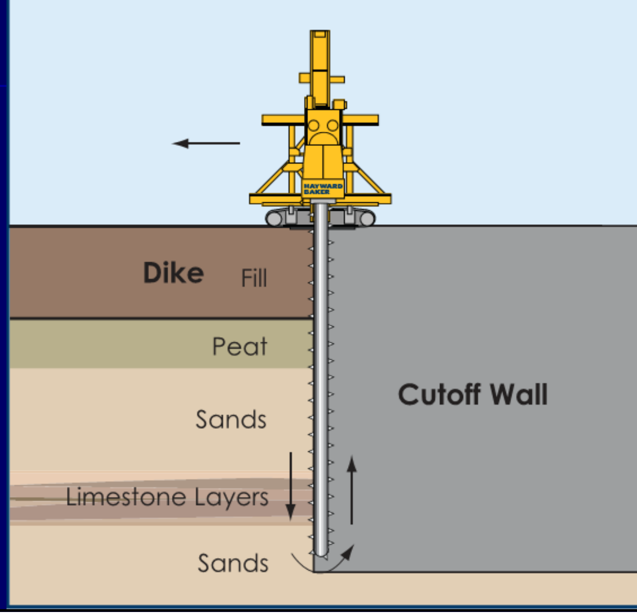
Cutter Soil Mixing (CSM)

In 2004 Bauer developed a new method to carry out Deep Soil Mixing. The method is based on the use of diaphragm wall cutters mounted to a special frame that is driven into the ground by a Kelly bar to produce rectangular panels of treated soil.





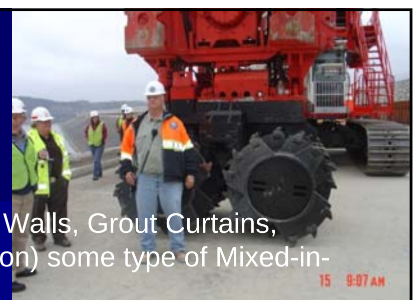
TRD Method



- Technology imported to the U.S. in 2006 by Hayward Baker and proved in the Alamitos Gap project in California soon after.
- Downwards/upwards ripping action provides very effective vertical homogenization of the soilcrete – a particular advantage in the very variable conditions at Herbert Hoover Dike.
- Extremely productive in appropriate soils conditions and weaker stratified rocks.

5. Final Remarks

- Large number of major dam safety incidents involving complex seepage/piping failure mode development processes.
- Timescales of different processes are highly variable
  - Solutioning of carbonates – millions of years
  - Solutioning of evaporites - < decade
  - Erosion of infilling in karst - < 1 engineer lifetime
- Potentially hundreds of existing “safe” dams may become unsafe in our lifetime.
- Goal of intervention/remediation is to create low (tolerable) risk profile.
- Since 1975 proven specialty construction technologies exist in North America to achieve this goal.



- These techniques include Concrete Walls, Grout Curtains, “Composite Walls,” and (less common) some type of Mixed-in-Place Wall.
- The most appropriate choice on any one project should ideally be dictated by the geology, the nature of the problems, and the performance goals of the remediation.
- For the good of the industry, it is essential that long-term performance information is published. (Federal Agencies and/or their A/E’s are best positioned to author these.)
- On each project, modifications to foreseen means and methods are inevitable, and prompt attention and resolution are essential.