Embankment Dams on Karstic Limestone, Soluble and Erodible Foundations: Challenges and Solutions

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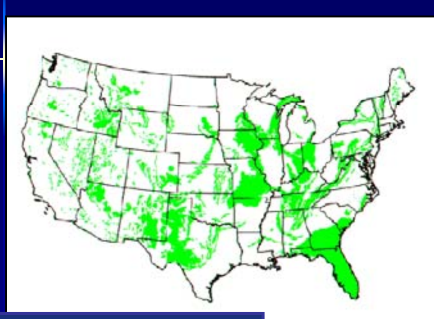
The Problem



USGS map of Karst in the US.

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

Centerhill Dam, TN – 1983 Muddy Show

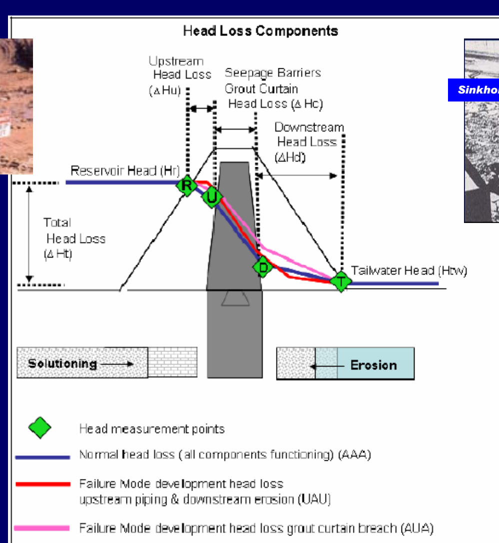
Clearwater Dam, MO – Sinkhole 15 January 2003

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



Failure Modes

Foundation or Bedrock	Failure Mode – Erosion	Failure Mode – Solutioning	Failure Mode – Combination Erosion and Solutioning	Example Projects
Karstic, Erodible	X			Wolf Creek, Center Hill, Clearwater, Arapuni
Soluble		X		Horsetooth, Quail Creek
Karstic/Erodible and Soluble			X	Mosul

Erosion Failure Modes

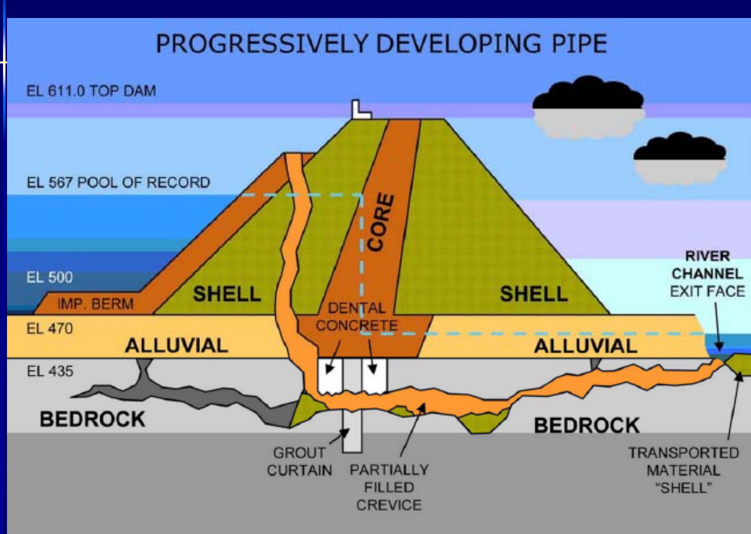


Figure courtesy of USACE

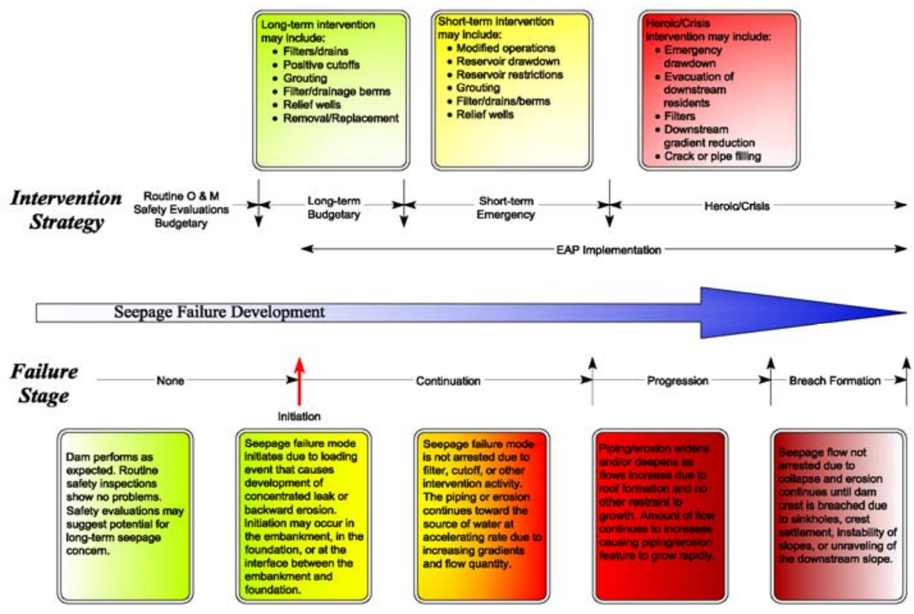
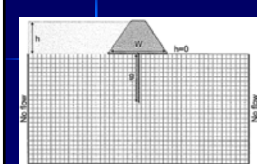
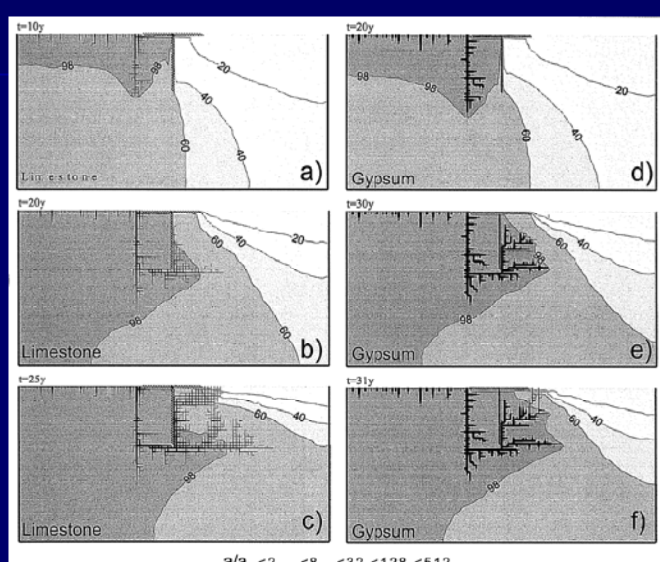


Figure 5
Seepage / Piping Failure Continuum

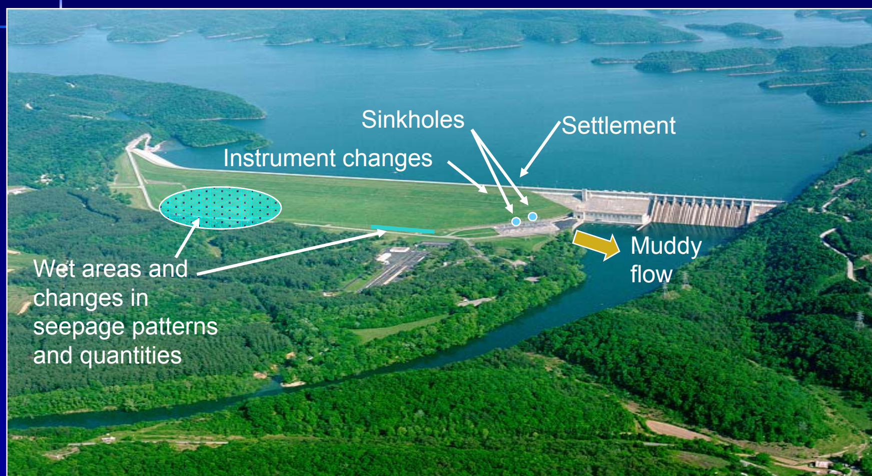
Solutioning Failure Modes





Source: Drybrodt et al, 2001

Distress Indicators



Factors Contributing to Location and Rate of Failure Mode Development

Geologic Characteristics of Karst, Erodible and Soluble Foundations

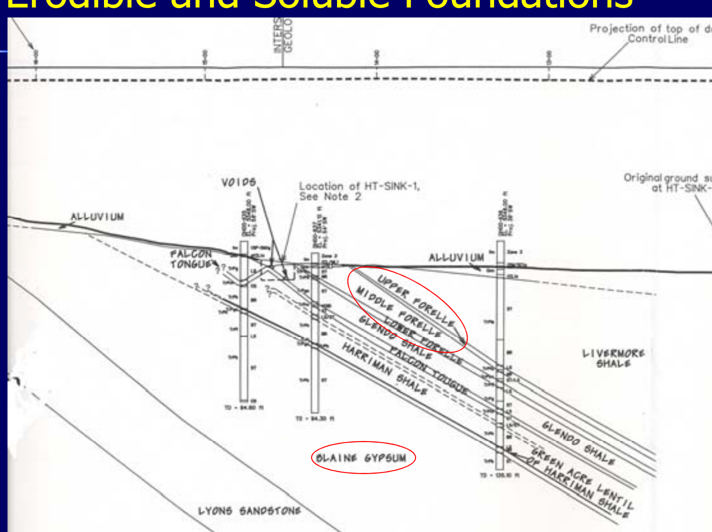
Structural Controlled Karst with connection to base of dam

Stratagraphically controlled Karst with no connection to base of dam

Clay Filling

Open flowing 20 to 30 gpm under low head

Geologic Characteristics of Karst, Erodible and Soluble Foundations



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

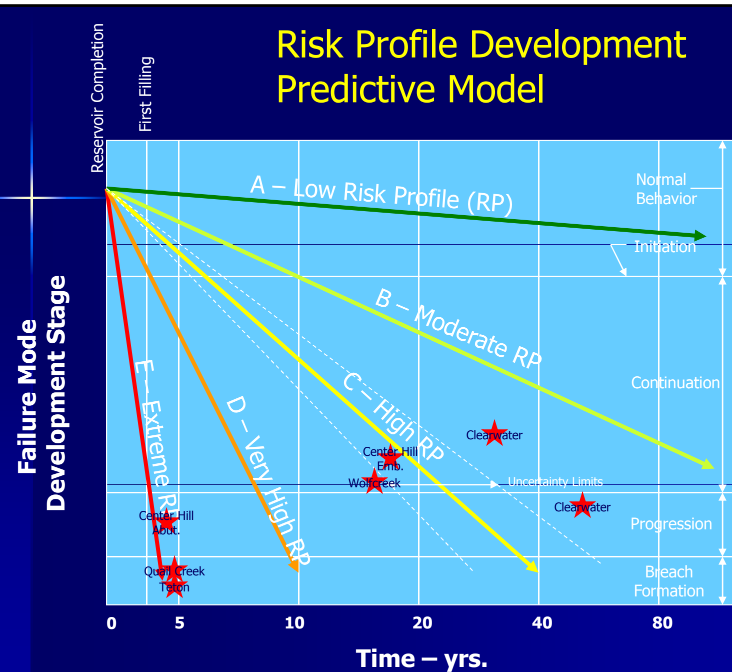
Left Abutment Sinkhole – Center Hill Dam

Site geology
Design Features
- Depth of foundation treatm
- 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.

Risk Profile Development Predictive Model



Solutions

Existing Dams

- Geologic models of site
- Modern grout curtains
- Composite cutoff wall systems
- Filters/Drains
- Replacement dams with adequate zonation and foundation treatments/cutoffs

Solutions

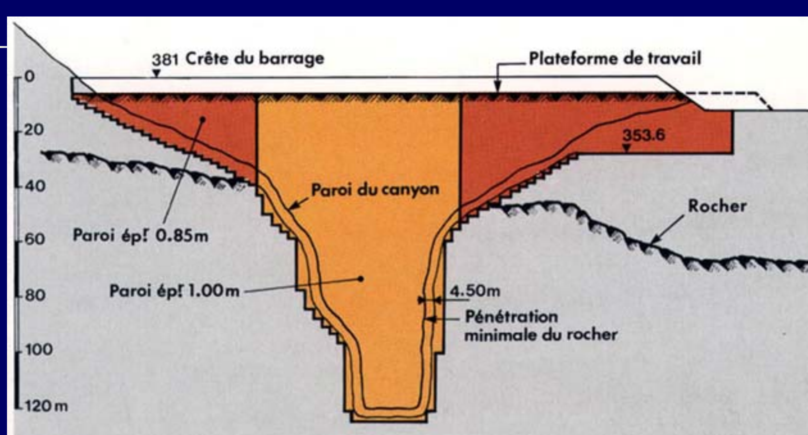
New Dams

- Excavation/treatment of defects
- Composite cutoff systems
- Concrete dams in lieu of embankments
- Combinations of the above

Review of Seepage Remediation Methodologies
Concrete Cut-Offs
Clamshells (cable or hydraulic)

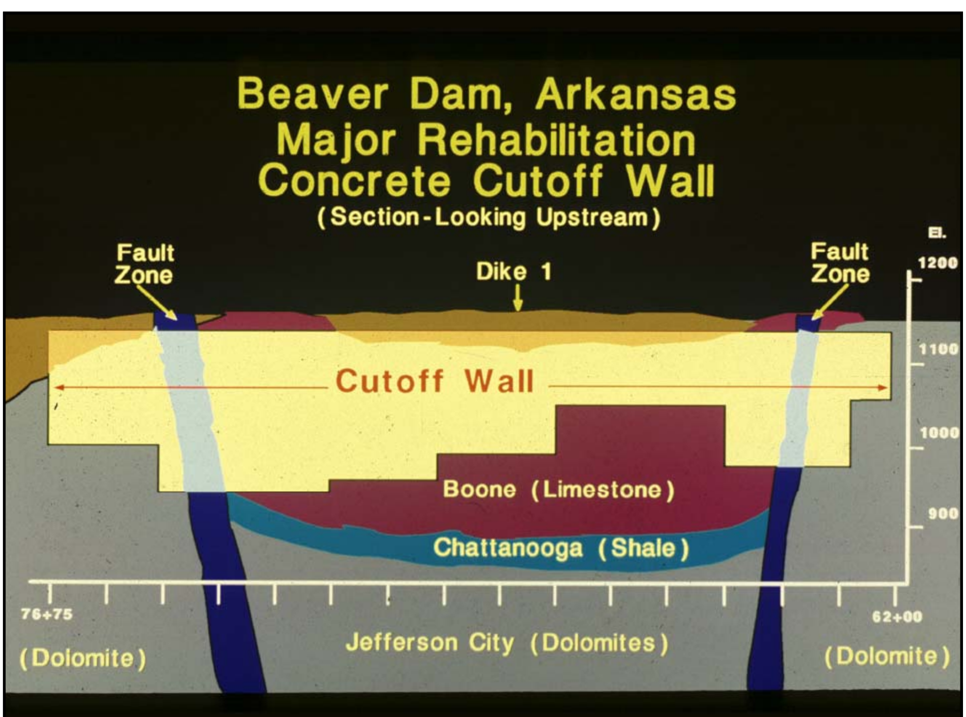
Hydromills/Cutters

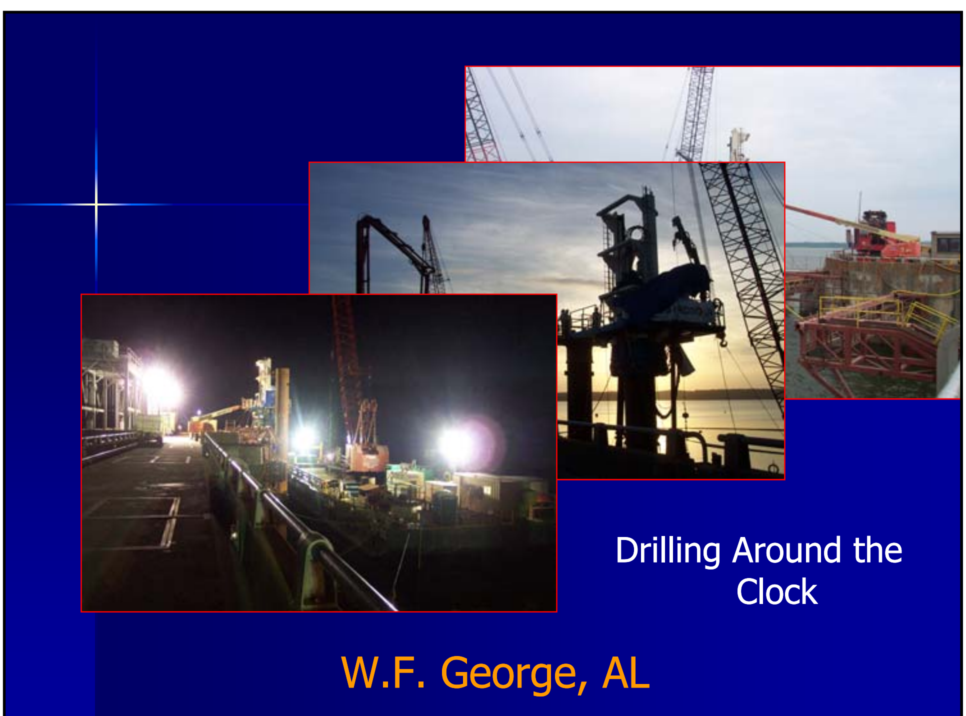
MUD MOUNTAIN



Secant Pile Method "Conventional"

Khao Laem Dam, Thailand





Drilling Around the Clock
W.F. George, AL

Secant Pile Method "Arapuni"

Field Trial, Rome, Italy

Field Trial, Rome, Italy

Technologies for "Soilcrete" or "Soft" Walls (not otherwise discussed in this presentation)

- 4.2.1 Deep Mixing
- 4.2.2 CSM Method
- 4.2.3 TRD Method
- 4.2.4 Backhoe

DMM Method

Deep mixing methods as they are known involve the use of a variety of cutting and mixing tools, mounted to one or more vertical shafts, that are driven into the ground to produce **columns** of treated soil.

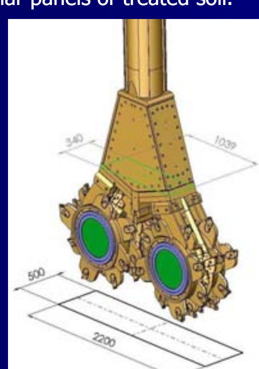


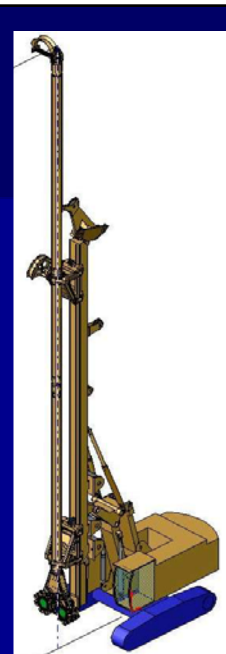


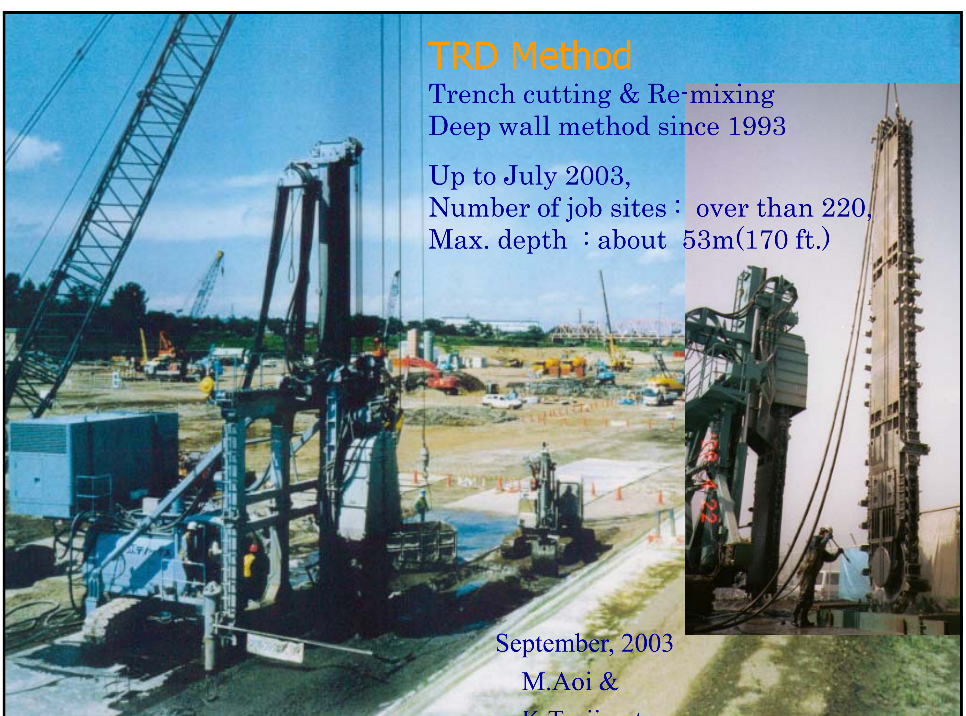
Some of the better known methods of deep mixing are summarized in the following chart:

Cutter Soil Mixing (CSM)

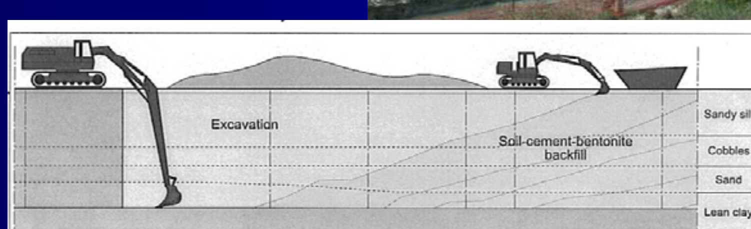
In 2004 Bauer developed a new method to carry out Deep Soil Mixing. The method is based on the use of diaphragm wall cutters mounted to a special frame that is driven into the ground by a Kelly bar to produce rectangular panels of treated soil.



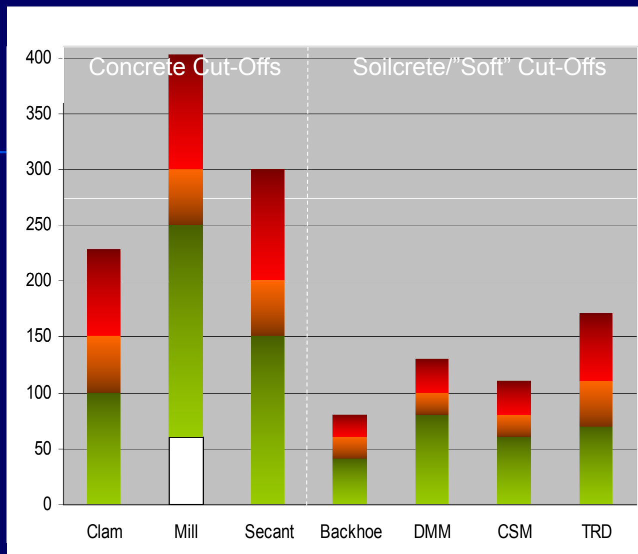



TRD Method
Trench cutting & Re-mixing
Deep wall method since 1993
Up to July 2003,
Number of job sites： over than 220,
Max. depth ：about 53m(170 ft.)
September, 2003
M.Aoi &
K.Tsujimoto
Blue print

Backhoe Method

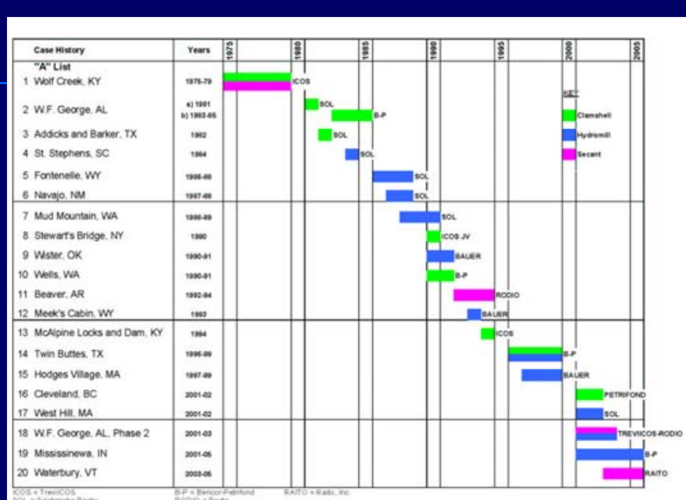


Typical cross section



Depth Capabilities of Different Cut-Off Methodologies

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



Concrete Cut-Offs for Existing Embankment Dams

Type of Construction	Number of Projects	Square Footage: Smallest	Square Footage: Largest	Square Footage: 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**

Note:

1. This is the cumulative result of 32 years of activity to date. During the next 5 years, USACE alone will likely conduct a similar dollar value again, on 3 dams.

Composite Grout/Concrete Cut-Offs

The New Way of Grouting

- 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

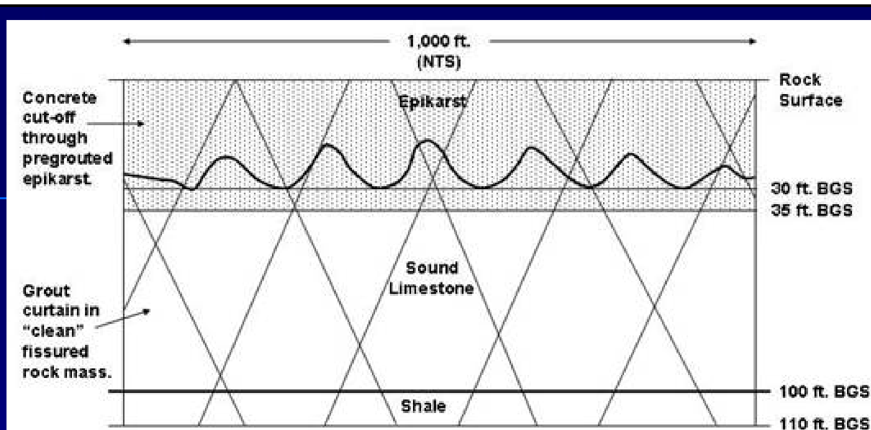
Clear example of equivalent performance of grouting to concrete cut-off wall construction.

Modern grouting can provide a high quality durable treatment in rock masses with clean fissures.

Systematic drilling and grouting of the conceptual concrete cut-off wall alignment

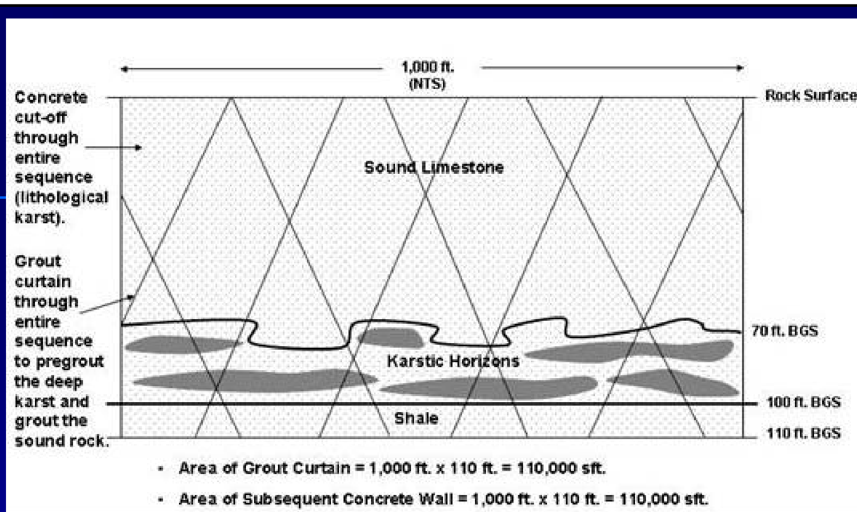
- **provides a very detailed geological picture (holes at effectively 5-foot centers as opposed to site investigation at, say 100-foot centers); this permits wall extent to be designed optimally;**
- **pretreats the epikarst (contact to mitigate against sudden, massive slurry loss during cut-off wall construction (to about 10 Lu);**
- **provides a durable, engineered cut-off in the "clean" rock below and beyond the concrete cut-off, at 5-10 times lower cost (to < 3 Lu).**

BEST OF BOTH WORLDS!

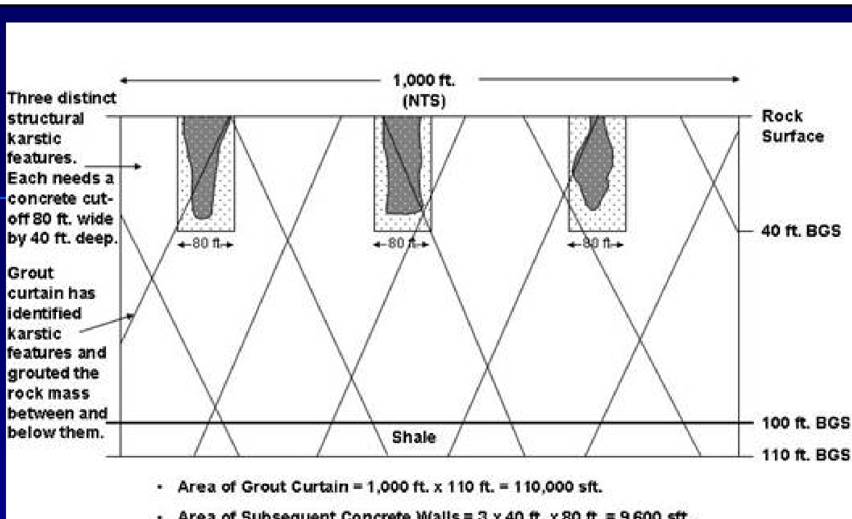


- Area of Grout Curtain (including pretreatment of epikarst) = 1,000 ft. x 110 ft. = 110,000 sft.
- Area of Subsequent Concrete Wall = 1,000 ft. x 35 ft. = 35,000 sft.

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.



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.



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.

Conclusions

- 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
- 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
- However, industry resources are currently stretched (especially human)
- Potentially hundreds of existing "safe" dams may become unsafe in our lifetime
- Authors are developing predictive model for assessing vulnerability and risk of these dams currently performing satisfactorily in these environments