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

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

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

Numerous other case histories exist
Failure Modes

Erosion Failure Modes

Figure courtesy of USACE
Distress Indicators for Existing Dams

- Sinkholes
- Settlement
- Wet areas and changes in seepage patterns and quantities
- Muddy flow
- Instrument changes
Geologic Characteristics of Karst, Erodible and Soluble Foundations

Stratigraphically controlled Karst with no connection to base of dam

Structural Controlled Karst with 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

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

- Pre-Excavate
- Excavate 1st Bite
- Excavate 2nd Bite
- Excavate 3rd Bite
- Place Concrete
- Complete Section

PRIMARY

SECONDARY
Concrete Cut-Off Walls Using Secant Piles

Clamshells
(Cable or Hydraulic)
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

Beaver Major Rehabilitation

Dike 1
Cutoff Wall Construction Area
U.S. Case Histories to Date

<table>
<thead>
<tr>
<th>Date Name and Site of Construction</th>
<th>Contractor</th>
<th>Type of Wall</th>
<th>Composition of Wall</th>
<th>Ground Containment</th>
<th>Purpose of Wall</th>
<th>Scope of Project</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WOLF CREEK, KY</td>
<td>IOS</td>
<td>CMU</td>
<td>Concrete</td>
<td>Damp-fill and ALUMINUM over groundwater resistant materials with a clay cap</td>
<td>To provide a physical barrier to contain stormwater, to separate the wetland from the land</td>
<td>24 in, Max. 30 ft</td>
<td>4,000 ft below surface level</td>
</tr>
<tr>
<td>2. W.T. GEORGE, AL</td>
<td>Subsurface</td>
<td>24-in.-thick poured cast-in-place concrete</td>
<td>3,000 yd</td>
<td>Silt-seal, Damp-fill and ALUMINUM over clay</td>
<td>To provide a positive barrier to contain stormwater, to separate the wetland from the land</td>
<td>24 in, Max. 13 ft</td>
<td>Approx. 3,000 ft</td>
</tr>
<tr>
<td>3. MOORESVILLE, NC</td>
<td>Subsurface</td>
<td>24-in.-thick poured cast-in-place concrete</td>
<td>3,000 yd</td>
<td>Silt-seal, Damp-fill over CLAY</td>
<td>To prevent drainage and seepage through core</td>
<td>36 in, Max. 10 ft to 92 ft</td>
<td>4,500 ft below surface level</td>
</tr>
</tbody>
</table>

*Siltseal have operated in the U.S. under different business identities over the years. “Siltseal” 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

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Number of Projects</th>
<th>Square Footage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Smallest</td>
</tr>
<tr>
<td>Mainly Clamshell</td>
<td>7</td>
<td>51,000</td>
</tr>
<tr>
<td>Mainly Hydromill</td>
<td>9</td>
<td>104,600</td>
</tr>
<tr>
<td>Mainly Secant Piles</td>
<td>4</td>
<td>12,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20</strong></td>
<td></td>
</tr>
</tbody>
</table>

2006-2013 Update

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

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.

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

Penetration distance controlled by pressure, cohesion, changing rheology, particle agglomeration, and/or bridging

Densification of Grout

Substantial water loss through pressure filtration

Post-grout Bleed Channels
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

- Refusal penetration controlled by pressure and cohesion
- Minor Densification of Grout
- Minimal water loss through pressure filtration
- Zero or Negligible Bleed Channels
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

Basic Principles

- Modern grouting methodologies can be relied upon to provide durable, effective cut-offs, provided 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 only where required.

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**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 only 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.
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
Cutoff Wall Techniques for Dams and Levees
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.