Review of Specialty Geotechnical Construction Techniques for Dams and Levees

by

Dr. Donald A. Bruce, Geosystems, L.P.
Scope of the Presentation

1. Introduction
2. Category 1 Cut-Offs (Excavate and Backfill)
3. Category 2 Cut-Offs (Mix in Place)
4. Overview
   • Focus on Pros/Cons/Limitations/Advantages
   • Research Needs Assessment
1. Introduction

Basic Classification

– Category 1 cut-offs created by backfilling a previously excavated trench, supported by bentonite (or polymer) slurry.

– Category 2 cut-offs created by mixing the levee and foundation soils in situ.
2. **Category 1 Cut-Offs (Excavate and Replace)**

- Intrinsic advantage is that resultant “backfill” material can be engineered, on the surface, and is virtually independent of the native material through which the cut-off has been excavated.

- Wide range of possible backfill materials:
  - Conventional Concrete (rare for levees).
  - Plastic Concrete.
  - Cement Bentonite (typically SHS).
  - Soil Bentonite.
  - Soil-Cement-Bentonite (Guidance provided in the paper).
Excavation Principles

- Panels (Clamshells or Hydromill)

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

- Excavate Single Bite
- Place Concrete
- Complete Section
Clamshells
(cable or hydraulic)
Cutters/Mills

Development of Trench Cutters
Panel Excavation

The cutters continuously remove the soil from the bottom of the trench, breaks it up and mixes it with a bentonite slurry in the trench.

The slurry charged with soil particles is pumped through a pipe to the de-sanding plant where it is cleaned and returned into the trench.
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**.
• Initially deployed in Paris in 1973, a hydrofraise was first used for a dam remediation by Soletanche, Inc. at St. Stephen Dam, SC, in 1984 (110,000 square feet).
• Thereafter, it had been used (by other contractors also) on 8 other major dam remediations in the U.S. prior to 2008, totaling about 2.4 million square feet.
Conventional Secant Pile Method
Beaver Major Rehabilitation

Dike 1
Cutoff Wall Construction Area
3. CUTOFF WALLS FOR DAMS

3.1 The Exceptional Nature of the Project

- Wolf Creek Dam, KY – a 3,940-foot-long homogeneous fill and contiguous 1,796-foot-long gated overflow section. Founded on Ordovician carbonates with major kastification. Retains Lake Cumberland and protects Tennessee.
• Designed in the 1930’s, built from 1941-1943 and 1945-1952.
• Severe hydraulic distress observed after impoundment leading to emergency grouting by USACE in 1968-1970 and 1973-1975.
• Primary Failure Mode related to erosion and piping of natural soft karstic infill materials and clay backfill in the core trench.
• Need for “definitive solution” led to international competition, won by ICOS Corporation of America in 1975. This successful solution for an existing dam featured a concrete diaphragm wall built by a unique combination of rotary drilling and clamshell excavation, both by then well established techniques.
First Solution – Cutoff Wall and Extensive Grouting Campaigns

ICOS Wall

Switchyard Wall

Diaphragm Wall

Grout Lines

Switchyard

Powerhouse

Switchyard Wall
First Solution – Cutoff Wall and Extensive Grouting Campaigns

ICOS’ barrier wall was installed along the centerline of the Embankment.

Approximately 990 Concrete to Steel Joints
• The main wall was 24 inches thick, 2,237 feet long, and a maximum of 280 feet deep. A secondary wall was built in the downstream switchyard.
• Built from 1975-1979 at a cost of 97 million dollars.
HOWEVER…

- During this original project, at least one member of the Board of Consultants (Dr. Peck) opined that the wall was neither deep enough nor long enough.

  …and of course he was correct.

- By January, 2007, Wolf Creek Dam was judged to merit a DSAC-1 rating – therefore requiring urgent and compelling action. The justification was a return of the classic distress symptoms.
Increasing Distress Indicators

- No. of Sinks: 3, 1
- No. of Wet Areas: 8, 8
- % of Wet Areas D/S: 0.2, 4.2
- Seepage Instability of River Bank Zones, No. of Locations: 0, 2
- No. of Artesian PZ's: 0, 6
- Cracks per 100 Feet at Road Surface (100'-1) Sta. 35+11-39+00: 4, 4
- Embankment Settlement (0.1'-1) Max Settlement at Station 37+00: 0, 3
- PZ Head (10%-1): 6, 7

1968 vs. 2004 comparison.
• Emergency grouting operation conducted as Phase 1 of the remediation in 2007-2008 by Advanced and Gannett Fleming as Phase 1 of a “Composite Wall” solution.

• Phase 2 involved the construction of a new cutoff upstream of the original, and longer and deeper, for an area of about 980,000 square feet – almost twice the original.

• Bid documents and specifications were Performance-based and emphasized Dam Safety in every process of the work, and urgency.

• It was obvious to all bidders that the technology of the 1970’s could not safely, reliably, or competitively satisfy the requirements of the 2008 project.

• The size, complexity and profile of the job attracted international attention from major prospective bidders.
The Solution by USACE

Foundation Drilling and Grouting

Cutoff Trench

Grout Curtain

Limestone Rc > 20000 psi

Elev. 550±

Soil Foundation

Lake

Elev. 475±

Existing Wall

Elev. 749 ft

TSJV Wall = 980,000 ft²

Elev. 680 ft

Pool

Cutoff Trench

Soil Foundation

Elev. 550±

Elev. 475±

Limestone Rc > 30,000 psi

Grout Curtain
3.2 Availability of the Technology

The Solution by the USACE

- Begins with 2-row grout curtain into rock (Advanced/Gannett Fleming)
- In late January 2007 → the USACE launches a $584 M remediation program
- In late 2008 → TSJV is awarded the main remediation contract for $341 M
- In the meantime → USACE maintains the pool elevation 80 ft below its maximum capacity
The Solution by TSJV

Protected Concrete Embankment Wall

- Secant Pile
- Directional Drilling

Wall C/L

- 3 ft
- 3 ft

Embankment

- Alluvium & Weathered Rock

Rock

- Strength between 10,000 and 36,000 psi
- Festures up to 40 ft in height
- Mixed rock/soil conditions
Hayward Baker were engaged to explore and pretreat the potentially vulnerable embankment/rock contact with a LMG operation, and to thereafter extend the Advanced/Gannett Fleming grout curtain.
Protective Concrete Embankment Wall
Directional Drilling
Secant Piles

- Following the directional drilling pilot hole. 50” piles installed at 31.5” or 35” centers
- Ensuring the required overlap and minimum thickness. – Max target depth 277-ft
Secant Pile Method “Arapuni”

Field Trial, Rome, Italy
First test panel, Arapuni, NZ
Excavation Principles
Continuous Wall (Backhoe)
Particular Advantages of Category 1 Cut-Offs

- Wide range of backfill properties.
- Can reach extreme depths:
  - 100 feet for backhoe
  - 250 feet for clamshell
  - 400 feet for hydromill
- Backhoe walls – where technically feasible – are very cost effective.
- All excavation methods and backfill types have long history of successful usage.
- In appropriate conditions, productivity can be high (> 3,000 sf/shift).
- Excellent pool of experienced contractors in the U.S.
Particular Potential Drawbacks of Category 1 Cut-Offs

- More spoil is created and must be handled/stored/disposed of.
- Backhoe walls are somewhat of a commodity, and QA/QC is always a concern (e.g., placement of SCB).
- Lateral continuity of panel walls (deviation, contamination).
- Sudden loss of slurry into large voids.

- Clamshell and hydromill operations need substantial working platform, guidewalls, slurry plants, etc.
- Hydromill walls are typically non-competitive except where special conditions exist (e.g., very hard layers, boulders, etc.).
# U.S. Case Histories – 1975-2016

<table>
<thead>
<tr>
<th>Dam Name and Year of Remediation</th>
<th>Contractor</th>
<th>Type of Wall</th>
<th>Composition of Wall</th>
<th>Ground Conditions</th>
<th>Purpose of Wall</th>
<th>Scope of Project</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WOLF CREEK, KY, 1975-1979</td>
<td>ICOS</td>
<td>24-inch diameter Primary Piles, joined by 24-inch wide clamshell panels. Two phases of work.</td>
<td>Concrete.</td>
<td>Dam FILL, and ALLUVIUM over argillaceous and karstic LIMESTONE with cavities, often clay-filled.</td>
<td>To provide a &quot;Positive concrete cut-off&quot; through dam and into bedrock to stop seepage, progressively developing in the karst.</td>
<td>Area: 270,000 sf (Phase 1) plus 261,000 sf (Phase 2)</td>
<td>Min. Width: 24 in</td>
</tr>
<tr>
<td>2. W.F. GEORGE, AL, 1981</td>
<td>Soletanche (Phase 1)</td>
<td>26-inch thick panels using cable and Kelly-mounted clamshell</td>
<td>Plastic concrete</td>
<td>Random, impervious FILL with silty core over 25-30 ft ALLUVIUM over chalky LIMESTONE</td>
<td>To provide a &quot;positive concrete cut-off&quot; through the dam and alluvials.</td>
<td>Area: 130,000 sf (Phase 1) plus 951,000 sf (Phase 2)</td>
<td>Min. Width: 26 in</td>
</tr>
<tr>
<td></td>
<td>Bencor-Petrofond (Phase 2)</td>
<td>24-inch panels 15-27 ft long</td>
<td>3,000 psi Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. ADDICKS AND BARKER, TX,</td>
<td>Soletanche*</td>
<td>36-inch thick panel wall with clamshell excavation using Kelly.</td>
<td>Soil-Bentonite.</td>
<td>Dam FILL over CLAY.</td>
<td>To prevent seepage and piping through core.</td>
<td>Area: 450,000 sf (Phase 1) plus 730,000 sf (Phase 2)</td>
<td>Min. Width: 36 in</td>
</tr>
<tr>
<td>Completed in 1982 (Phase 1 took 5 months)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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 to 2016

<table>
<thead>
<tr>
<th>Case History</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot; List</td>
<td></td>
</tr>
<tr>
<td>1 Wolf Creek, KY</td>
<td>1975-79</td>
</tr>
<tr>
<td>2 W.F. George, AL</td>
<td>a) 1981, b) 1983-85</td>
</tr>
<tr>
<td>3 Addicks and Barker, TX</td>
<td>1982</td>
</tr>
<tr>
<td>4 St. Stephens, SC</td>
<td>1984</td>
</tr>
<tr>
<td>5 Fontenelle, WY</td>
<td>1986-88</td>
</tr>
<tr>
<td>6 Navajo, NM</td>
<td>1987-88</td>
</tr>
<tr>
<td>7 Mud Mountain, WA</td>
<td>1988-89</td>
</tr>
<tr>
<td>8 Stewart's Bridge, NY</td>
<td>1990</td>
</tr>
<tr>
<td>9 Wister, OK</td>
<td>1990-91</td>
</tr>
<tr>
<td>10 Wells, WA</td>
<td>1990-91</td>
</tr>
<tr>
<td>11 Beaver, AR</td>
<td>1992-94</td>
</tr>
<tr>
<td>12 Meek's Cabin, WY</td>
<td>1993</td>
</tr>
<tr>
<td>13 McAlpine Locks and Dam, KY</td>
<td>1994</td>
</tr>
<tr>
<td>14 Twin Buttes, TX</td>
<td>1996-99</td>
</tr>
<tr>
<td>15 Hodges Village, MA</td>
<td>1997-99</td>
</tr>
<tr>
<td>16 Cleveland, BC</td>
<td>2001-02</td>
</tr>
<tr>
<td>17 West Hill, MA</td>
<td>2001-02</td>
</tr>
<tr>
<td>18 W.F. George, AL, Phase 2</td>
<td>2001-03</td>
</tr>
<tr>
<td>19 Mississinewa, IN</td>
<td>2001-05</td>
</tr>
<tr>
<td>20 Waterbury, VT</td>
<td>2003-05</td>
</tr>
<tr>
<td>21 Herbert Hoover, FL</td>
<td>2007-13</td>
</tr>
<tr>
<td>22 Clearwater, MO</td>
<td>2008-11</td>
</tr>
<tr>
<td>23 Wolf Creek, KY</td>
<td>2008-13</td>
</tr>
<tr>
<td>24 Center Hill, TN</td>
<td>2012-14</td>
</tr>
<tr>
<td>25 Bolivar, OH</td>
<td>2014-2016</td>
</tr>
<tr>
<td>26 Pine Creek, OK</td>
<td>2016</td>
</tr>
<tr>
<td>27 East Branch, PA</td>
<td>2017 onwards</td>
</tr>
</tbody>
</table>
Category 1 Concrete Cut-Offs for Existing Embankment Dams (1975-2005)

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Number of Projects</th>
<th>Square Footage</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Smallest</td>
<td>Largest</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Mainly Clamshell</td>
<td>7</td>
<td>51,000</td>
<td>1,400,000</td>
<td>3,986,320</td>
<td></td>
</tr>
<tr>
<td>Mainly Hydromill</td>
<td>9</td>
<td>104,600</td>
<td>850,000</td>
<td>2,389,415</td>
<td></td>
</tr>
<tr>
<td>Mainly Secant Piles</td>
<td>4</td>
<td>12,000</td>
<td>531,000</td>
<td>1,050,700</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
<td></td>
<td></td>
<td>7,426,435</td>
<td></td>
</tr>
</tbody>
</table>

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.
3. Category 2 Cut-Offs (Mix in Place)

DMM (Deep Mixing Methods)

- Rotary Vertical Axis
- Jet Assisted Vertical Axis (Turbojet)
- Continuous Trench Cutting
  - TRD
  - “One Pass”
- Horizontal Axis Cutting and Mixing
  - Low Pressure (CSM)
  - High Pressure (CT Jet)

- Wet End Mix
- Wet Shaft Mix
- Dry End Mix

“Conventional”
Conditions Favoring DMM

- Ground is neither very stiff or very dense
- Ground has no boulders/obstructions
- Treatment < 40 m depth
- Unrestricted overhead clearance
- Good and constant binder source
- Large spoil volumes can be tolerated
- Vibrations are to be avoided
- Treated soil volumes are large
- “Performance Specifications” applicable
- Treated ground parameters well defined
“Conventional” DMM

Particular Advantages

- Low vibration, moderate noise.
- Applicable in most soil conditions.
- In appropriate conditions, good homogeneity and continuity can be achieved.
- Productivities can be high – 2,000/3,000 sf/shift.
- Unit prices are low - moderate.
- Several good, experienced contractors in the U.S.
“Conventional” DMM

Potential Drawbacks

- Large, heavy equipment.
- Practical depth 110 feet (vertical).
- Method sensitive to very dense or stiff soil, organics, boulders.
- Mobilization/demobilization costs high.
Continuous Trench Cutting

TRD (Trench Re-Mixing and Cutting Deep Wall) Method

- Conceived in 1993 in Japan.
- First used in U.S. in 2005.
- 170 ft. depth capability, 18-34 inches wide.
- Continuous wall created by lateral motion of vertical “chain saw,” installed in a predrilled hole.
Blades vary according to soil condition

A) Standard blade
B) Rounding blade for hard clay
C) Long-nosed blade for boulder
**TRD**

**Particular Advantages**

- Continuous, homogeneous, joint-free wall in all soil and many rock conditions.
- Productivities can be extremely high (instantaneous production > 400 sft/hour).

- High degree of real time QA/QC.
- Adjustability of cutting teeth.
- Can operate in low headroom (20 ft).
- Very quite, modest size support equipment, “clean” operation.
TRD

Potential Drawbacks

- Sharp alignment changes.
- Especially hard/massive/abrasive rock.
- Trapping of “post” in soilcrete or “refusal” on boulders/rock.
- Only one (excellent) contractor!
“One Pass” System (DeWind)
CSM (Cutter Soil Mix) Method

- Joint Bauer Maschinen/Bachy Soletanche development in 2003
- Combines expertise in hydromill and deep mixing.
- Rapidly increasing in popularity worldwide (over 30 units in service).
- Similar system developed by Trevi (CT Jet).
- Maximum depth 180 feet, 20-47 inches wide.
The CSM machine is fitted with a set of instruments that convey to the operator, in real time, all the information that is needed to monitor and control quality of the work.

External pressure sensor

Instruments that read:
- Verticality on “X” and “Y” axes
- Torque on cutting wheels
- Wheel speeds

BAUER B-Tronic system
CSM

Particular Advantages

- Continuity assured by very strict verticality control.
- Very homogeneous product.
- Applicable in all soil conditions (peat should be removed).
- Adjustable teeth.
- CSM can be mounted on non-specialized carriers.
- Productivity can be very high.
- Can accommodate sharp alignment changes.
- Quiet and vibration free.
CSM

Potential Drawbacks

• As for all DMM variants, rock, boulders and organics are challenges.
• Needs considerable headroom.
• Cost base (as for all DMM variants).
## Overview of Category 2 Walls

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Wall Dimensions</th>
<th>Properties of Backfill</th>
<th>Costs</th>
<th>Relative Benefits/Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>Width</td>
<td>UCS</td>
</tr>
<tr>
<td><strong>Category 1 — Excavate and Replace (i.e., under bentonite slurry)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clamshell</td>
<td>Various types of clams can be used to remove soil in panels</td>
<td>Max 250'</td>
<td>16-66</td>
<td>24-36</td>
<td>Low</td>
</tr>
<tr>
<td>Hydromill</td>
<td>Large frame with cutting wheels and reverse circulation mud pump to remove soil in panels</td>
<td>Max over 400'</td>
<td>24-60</td>
<td>33-39</td>
<td>Moderate</td>
</tr>
<tr>
<td>Backhoe</td>
<td>Modified long reach excavator to create continuous trench</td>
<td>Max 100'</td>
<td>30-36</td>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td><strong>Category 2 — Mix in Place</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional DMM</td>
<td>Vertically mounted shafts are rotated into the soil creating panels of soilcrete</td>
<td>Maximum practical about 110'</td>
<td>20-40</td>
<td></td>
<td>100-1,500 psi</td>
</tr>
</tbody>
</table>

(continues)
<table>
<thead>
<tr>
<th>METHOD</th>
<th>PRINCIPLE</th>
<th>WALL DIMENSIONS</th>
<th>PROPERTIES OF BACKFILL</th>
<th>COSTS</th>
<th>RELATIVE BENEFITS/PROBLEMS</th>
</tr>
</thead>
</table>
| TRD    | Vertical chainsaw providing simultaneous cutting and mixing of soil to produce continuous soilcrete wall | Maximum 170’, 18-34” | 100-3,000 psi | 10⁶ to 10⁹ cm/s | Moderate to Very High, Moderate to High | - Continuity of cut-off is automatically assured  
- Homogeneity  
- Speed  
- Quality  
- Adaptability to wide range of ground conditions  
- Low noise and vibrations  
- Low headroom potential  
- Inclined diaphragms possible  
- Wide range in cut-off properties can be engineered |
| CSM    | Cutting and mixing wheels mounted on horizontal axes create vertical soilcrete panels (Deeper and wider with CT Jet variant) | Max 180’, 20-47” | 100-3,000 psi | 10⁶ to 10⁹ cm/s | Low to Moderate, Moderate | - Panel continuity/verticality  
- Homogeneity  
- Speed  
- Adaptable to conventional carriers  
- Wide range in cut-off properties can be engineered  
- Can accommodate sharp geometry changes |

**Key to Costs**

<table>
<thead>
<tr>
<th>Mob/Demob</th>
<th>Unit Costs (i.e., cost per square foot of cut-off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; $50,000</td>
<td>Very Low</td>
</tr>
<tr>
<td>$50,000-$150,000</td>
<td>Low</td>
</tr>
<tr>
<td>$150,000-$300,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>$300,000-$500,000</td>
<td>High</td>
</tr>
<tr>
<td>&gt; $500,000</td>
<td>Very High</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit Costs</th>
<th>Mob/Demob</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; $10</td>
<td>Very Low</td>
</tr>
<tr>
<td>$10-$20</td>
<td>Low</td>
</tr>
<tr>
<td>$20-$50</td>
<td>Moderate</td>
</tr>
<tr>
<td>$50-$100</td>
<td>High</td>
</tr>
<tr>
<td>&gt; $100</td>
<td>Very High</td>
</tr>
</tbody>
</table>
Feet

Green – Typical range
Orange – Less common but still relatively straightforward
Red – Extensive situations
White – Not feasible
Acknowledgements

Dick Davidson (URS)
Jim Hussin/George Burke (HAYWARD BAKER)
Brian Jasperse (GEOCON)
Mario Mauro (TREVIICOS)
Al Neumann (formerly BAUER, now Bencor)
Lis Smith (DeWind)
Gilbert Tallard
David Yang (RAITO)
USACE

Dedicated to the memory of our late friends,
Renato Fiorotto, formerly of Casagrande Bauer Maschinen
and Arturo Ressi, The ICOS Corporation
New Data Source

Chapters on:

- Drilling and Grouting Cutoffs
- Category 1 Cutoffs (Concrete)
- Category 2 Cutoffs (DMM)
- Composite Walls
- Anchors
- Instrumentation