1. Introduction and General Background

- Over 84,000 dams in U.S.
- 14,000 meet “high hazard” criterion (loss of one or more human life)
- Median age 64 years
- 27,000 km end to end
- Perhaps around 180,000 km of levees, of which barely 15% are “Federal”

Fundamental challenges are posed to our dams and levees by:

- Geology: 40% of contiguous states underlain by evaporites/karst
- Seismicity: New Madrid, MO and Charleston, SC, as well as Western U.S.
- Aging/maintenance funding
- Natural disasters

Basic Classification of Cutoffs

- 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.

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**Excavation Principles**
- Panels (Clamshells or Hydromill)

- Clamshells (cable or hydraulic)

- Development of Trench Cutters

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**Cutters/Mills**

- Development of Trench Cutters
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.

Hydrofrases have been used in remedial works to a maximum depth of over 400 feet (Mud Mountain Dam, WA) and have recently been tested to over 800 feet in a test at Gualdo, Italy, to within 0.13% verticality.

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.
Conventional Secant Pile Method

Beaver Major Rehabilitation
Dike 1
Cutoff Wall Construction Area

W.F. George, AL
Concrete Cut-Off Walls Using Secant Piles

**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.).
CASE HISTORY: WOLF CREEK DAM, KY

- 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.

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

- Recent technological developments have focused on reliability, productivity, and verticality monitoring and control.

- The experience of the partners in Wolf Creek 2 was combined to provide the successful solution:
  - A 6-foot-wide, 535,000 sf “disposable” diaphragm wall constructed by hydromill through the embankment and just into the bedrock: the “Protective Concrete Embankment Wall” (PCEW), and
  - The actual cutoff created in the underlying karst by drilling 1,197 guided 50-inch diameter secant elements through the PCEW.

The Solution by TSJV
U.S. Case Histories – 1975-2005

**Category 1 Concrete Cut-Offs for Existing Embankment Dams**

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Number of Projects</th>
<th>Smallest</th>
<th>Largest</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainly Clayshell</td>
<td>7</td>
<td>51,000</td>
<td>1,400,000</td>
<td>3,980,329</td>
</tr>
<tr>
<td>Mainly Rockfill</td>
<td>9</td>
<td>104,609</td>
<td>850,000</td>
<td>2,398,415</td>
</tr>
<tr>
<td>Mainly Silt Fill</td>
<td>4</td>
<td>12,000</td>
<td>531,060</td>
<td>1,059,709</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>20</td>
<td><strong>7,425,435</strong></td>
<td></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.

**Category 2 Cut-Offs (Mix in Place)**

- **DMM (Deep Mixing Methods)**
  - **Rotary Vertical Axis**
  - **Jet Assisted Vertical Axis (Turbojet)**
  - **Trench Cutting and Mixing (TRD)**
  - **Horizontal Axis Cutting and Mixing**
  - **Low Pressure (CSM)**
  - **High Pressure (CT Jet)**

**Q&A**

“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.

**Potential Drawbacks**

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

During hurricane Katrina a substantial percentage of New Orleans East Levee System failed, including LPV111. The Hurricane Protection Office of the US Army Corps of Engineers attributed the failure of the system to overtopping, erosion, and subsequent breaching of levees along the GIWW.

**LPV 111 Project Overview**

In order to address the technical and logistical demands of the project, deep mixing method was designed as the most suitable technology utilizing “Early Contractor Involvement”. 
Recycled Embankment Material (REM) is produced during DMM
AWA prepares the working platform for the DMM to be performed
TREVIICOS Corporation
38 Third Avenue, 3rd Floor – Boston National Historic Park-Charlestown, MA
Design Technology
Over 60% of the ground improvement was accomplished with the Trevi Turbo Mix technology, single and double axis.
The TTM method is a recent development of the deep mixing technology. It combines the injection of cement slurry at high velocity into the ground with mechanical mixing of the rotating blades.
The additional energy provided by the grout jets greatly improves the quality of the mixing of the soil with the grout and reduces the time required for the installation of the soil-mix columns.
Pre-Construction
The contract required that pre-construction activities be performed during the design phase to determine the most appropriate construction parameters and technical solutions:
- Soil Investigation (2 phases)
- Desk Study
- Bench Scale mixing program (4 phases)
- Field Validation Test program (5+ phases)
Due to schedule constraints, only the first stages of the pre-construction activities were accomplished before the beginning of the actual production. The remaining stages were performed as work areas became available.

Production
Some numbers…

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCTION START DATE</td>
<td>1/14/2010</td>
</tr>
<tr>
<td>PRODUCTION COMPLETION DATE</td>
<td>3/18/2011</td>
</tr>
<tr>
<td>TOTAL CALENDAR DAYS</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL MONTHS</td>
<td>14.43</td>
</tr>
<tr>
<td>TOTAL SHEETS WORKED (as of 3/18/2011)</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL MANHOURS (as of 3/18/2011)</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL DMM ELEMENT INSTALLED</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL VOLUME TREATED CY</td>
<td>1,681,579</td>
</tr>
<tr>
<td>TOTAL CEMENT USED SHTON</td>
<td>457,693</td>
</tr>
<tr>
<td>TOTAL TRUCK-LOADS (approx)</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL WATER USED GAL</td>
<td>136,332,094</td>
</tr>
<tr>
<td>TOTAL COREING</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL UCS TESTS</td>
<td>N</td>
</tr>
<tr>
<td>OVERALL AVERAGE UCS (required &lt;100 psi)</td>
<td>PSI</td>
</tr>
<tr>
<td>TOTAL FAILING UCS TESTS (&lt;100 psi)</td>
<td>N</td>
</tr>
<tr>
<td>TOTAL FAILING UCS TESTS (10% allowed)</td>
<td>%</td>
</tr>
</tbody>
</table>

…that makes LPV111 the largest land-based deep soil mixing job ever undertaken outside of Japan

Construction
LPV 111 CHALLENGES:
schedule – logistics – design – soil characteristics – size of the job

- 2x12 hrs/shifts, 5.5 days/week
- 6 dual auger + 2 single auger rigs
- 8 active batch plants producing ≈50 cy/hr of grout
- approximately 460,000 tons of cement used → 17,500 trucks
- 3 coring rigs
- over 500,000 man-hours in 14 months of production

Some numbers…

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<td>%</td>
</tr>
</tbody>
</table>

…that makes LPV111 the largest land-based deep soil mixing job ever undertaken outside of Japan
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 quiet, 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!

**DeWind "One Pass Trenching"**

<table>
<thead>
<tr>
<th>Width (inches)</th>
<th>Depth (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>45</td>
</tr>
<tr>
<td>24</td>
<td>45</td>
</tr>
<tr>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>32</td>
<td>125</td>
</tr>
<tr>
<td>36</td>
<td>115</td>
</tr>
<tr>
<td>51</td>
<td>80</td>
</tr>
</tbody>
</table>
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.

CSM (Cutter Soil Mix) Method
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.

### CSM Quality Control Systems

- External pressure sensor
- Instruments that read:
  - Verticality on "X" and "Y" axes
  - Torque on cutting wheels
  - Wheel speeds

- 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.

### 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>Advantages</th>
<th>Disadvantages</th>
<th>Risk</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMT</td>
<td>Cut and monopolize the ground</td>
<td>Low cost, high efficiency</td>
<td>High cost, complex setup</td>
<td>High</td>
<td>Used in hard ground</td>
</tr>
<tr>
<td>TBM</td>
<td>Tunnel boring machine</td>
<td>Quiet, no noise</td>
<td>High cost, complex setup</td>
<td>High</td>
<td>Used in soft ground</td>
</tr>
</tbody>
</table>

Acknowledgements

Dick Davidson (URS)
Jim Hussin/George Burke (HAYWARD BAKER)
Brian Jasperse (formerly GEOCON)
Charlie Krug (DeWIND)
Mario Mauro and Stefano Valagussa (TREVIICOS)
Al Neumann (formerly BAUER, now LAYNE)
Gilbert Tallard
David Yang (JAFEC)
USACE

Dedicated to the memory of our late friends, Renato Fiorotto, formerly of Casagrande and Bauer Maschinen, and Arturo Ressi, ICOS

New Data Source

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

Q&A