Review of Specialty Geotechnical Construction Techniques for Dams and Levees

by

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Specialty Geotechnical Workshop for Dam + Levee Investigations + Modifications

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ENVIRONMENTAL ENGINEERING GEOLOGISTS AEG

USSD

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

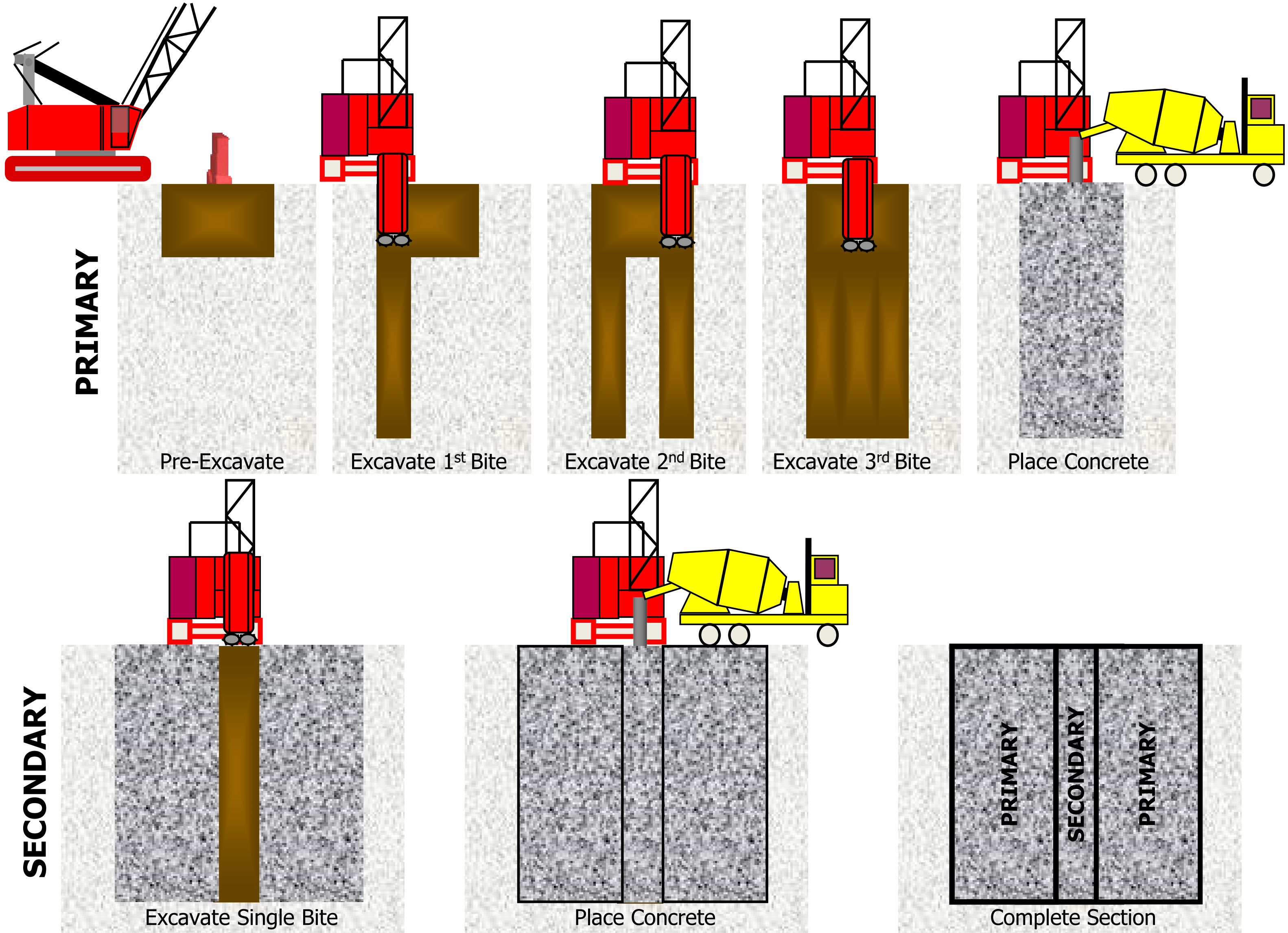
Basic Classification

- 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).

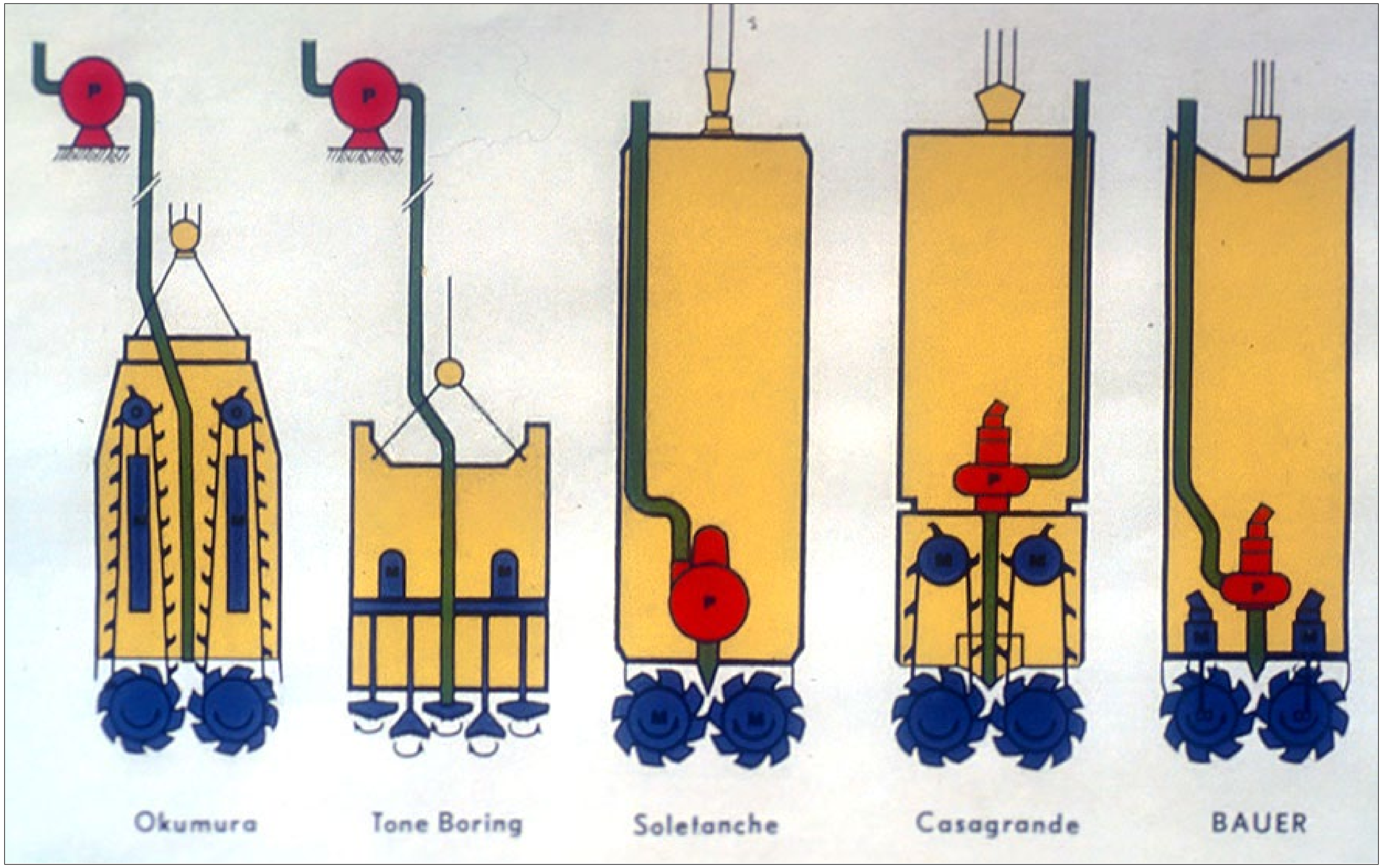
- Excavation Principles
  - Panels (Clamshells or Hydromill)



Clamshells
(cable or hydraulic)


ADONEL
Beach Division

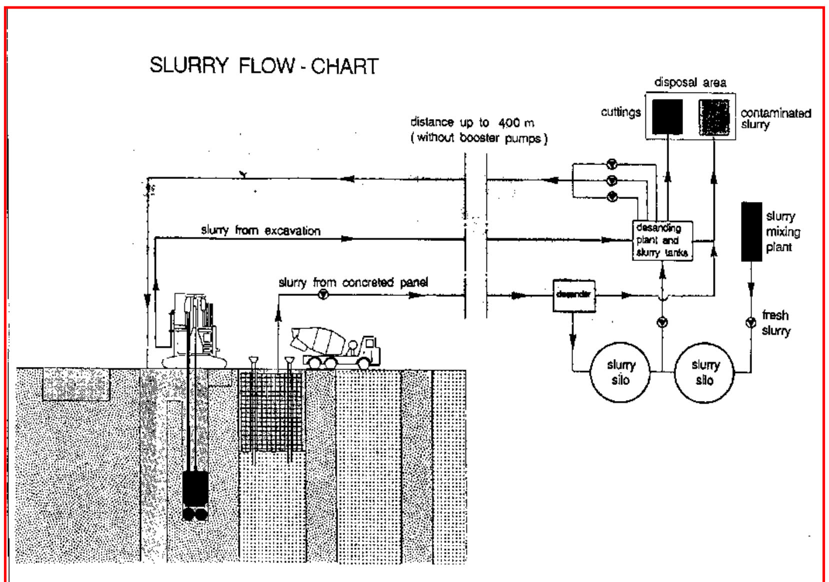
Cutters/Mills



Development of Trench Cutters

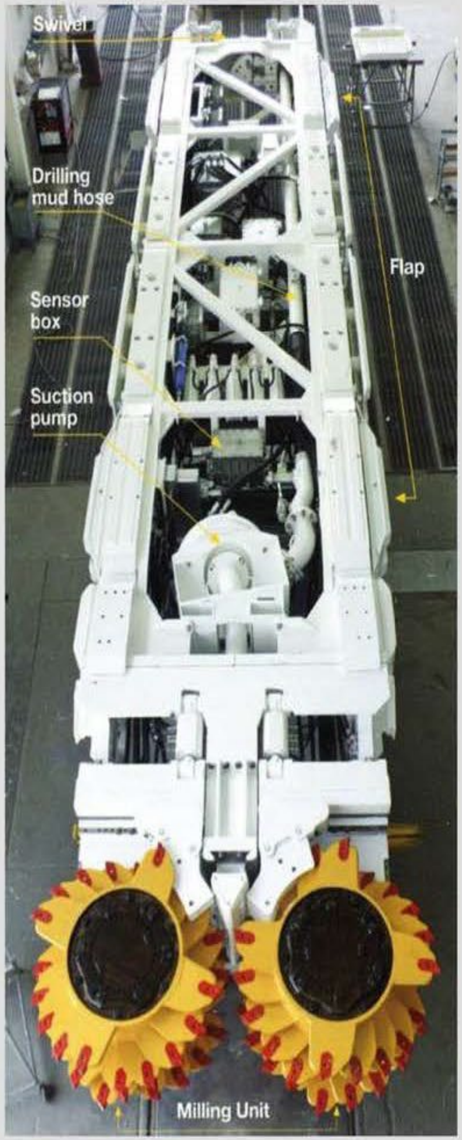
- Panel Excavation

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.



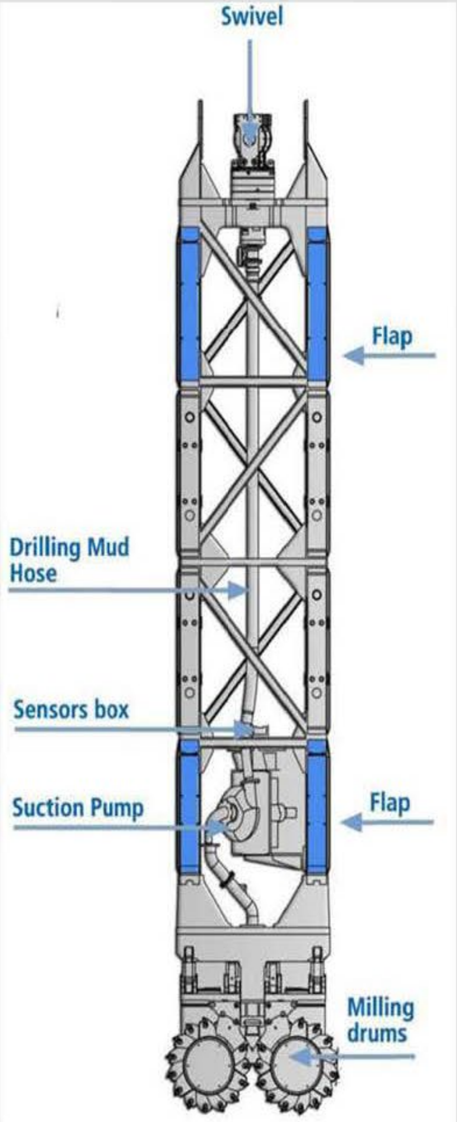
The slurry charged with soil particles is pumped through a pipe to the de-sanding plant where it is cleaned and returned into the trench.

HYDROMILL TECHNOLOGY

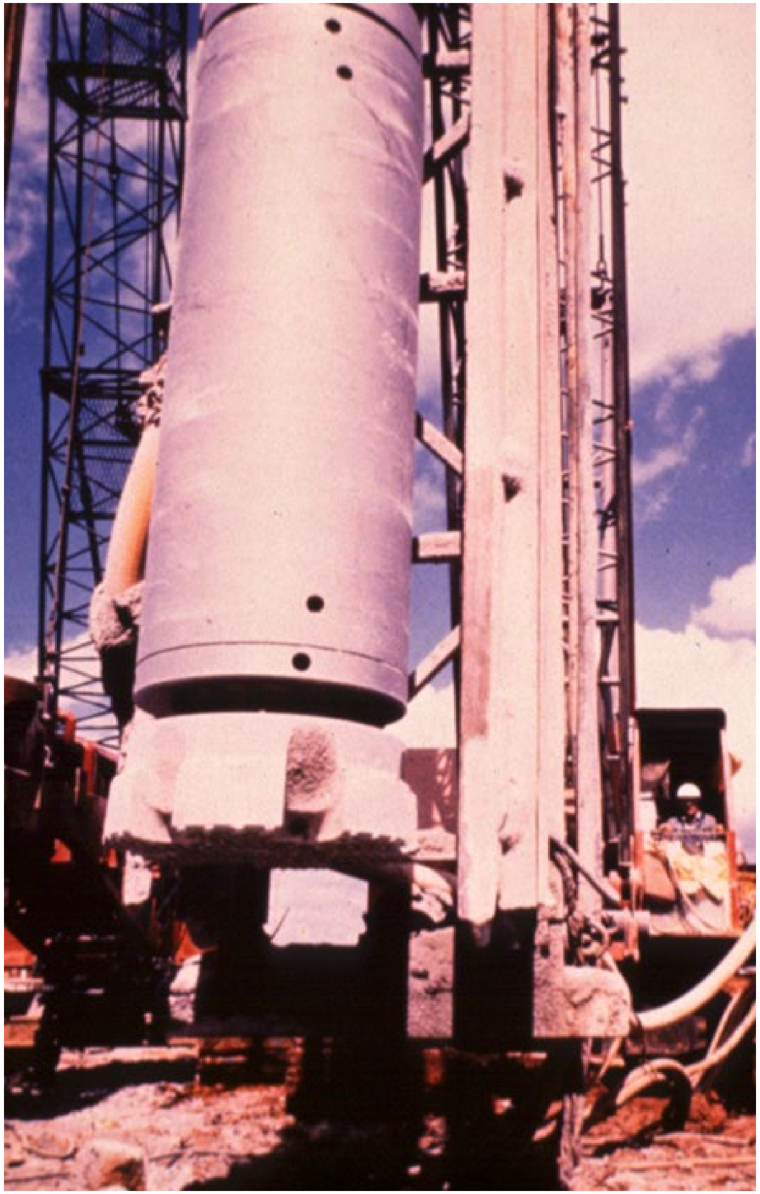


The core of any Hydromill is its trenching/cutting unit, that schematically consists of a heavy steel frame integrating the following components:

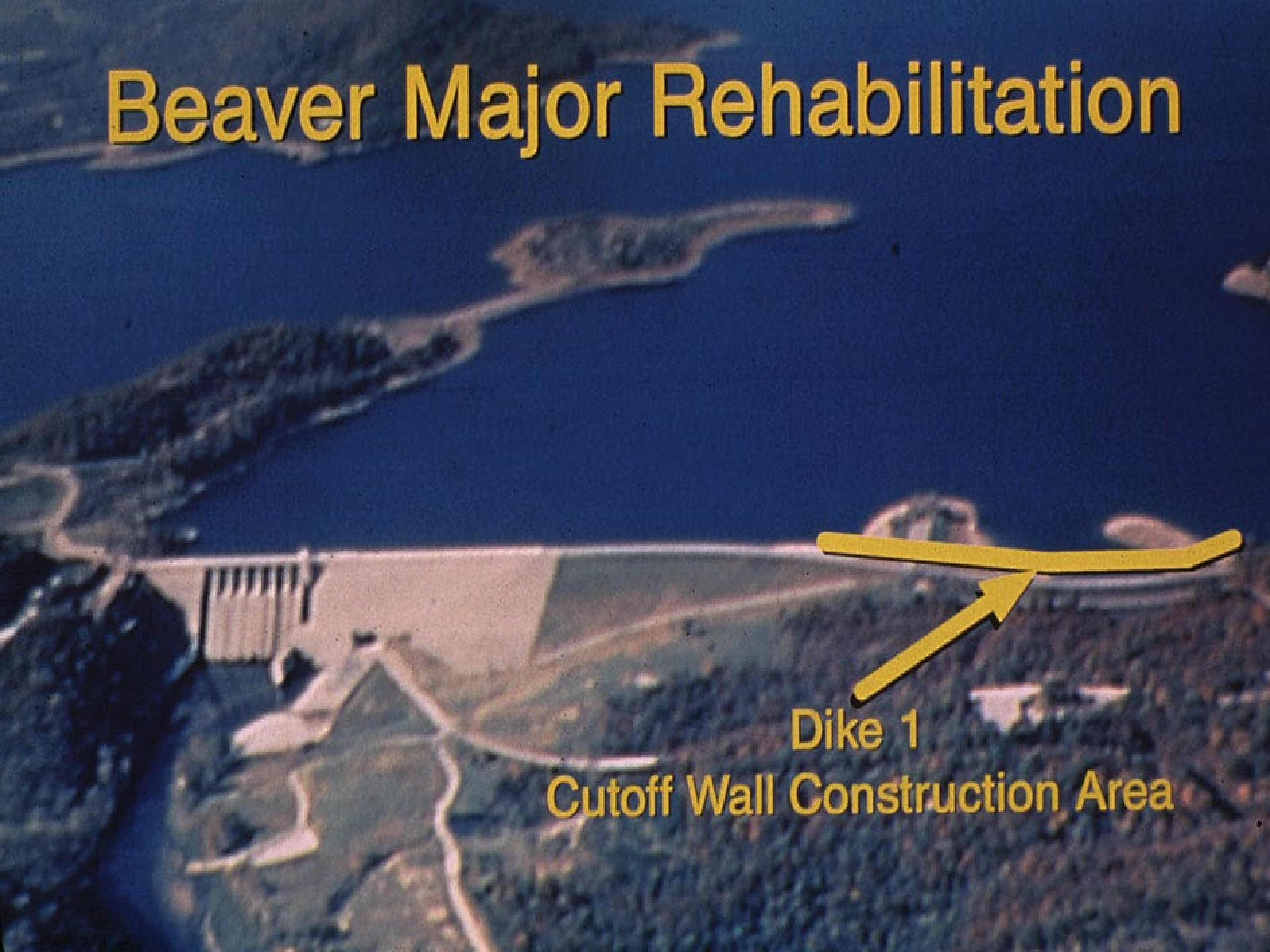
- swivel located on top of the frame
- two independent hydraulic engines which allows the rotation of a pair of milling drums located at the bottom of the frame;
- a mud suction pump placed just above the milling wheels;
- front and side hydraulically-operated "steering" flaps;
- a number of built-in 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

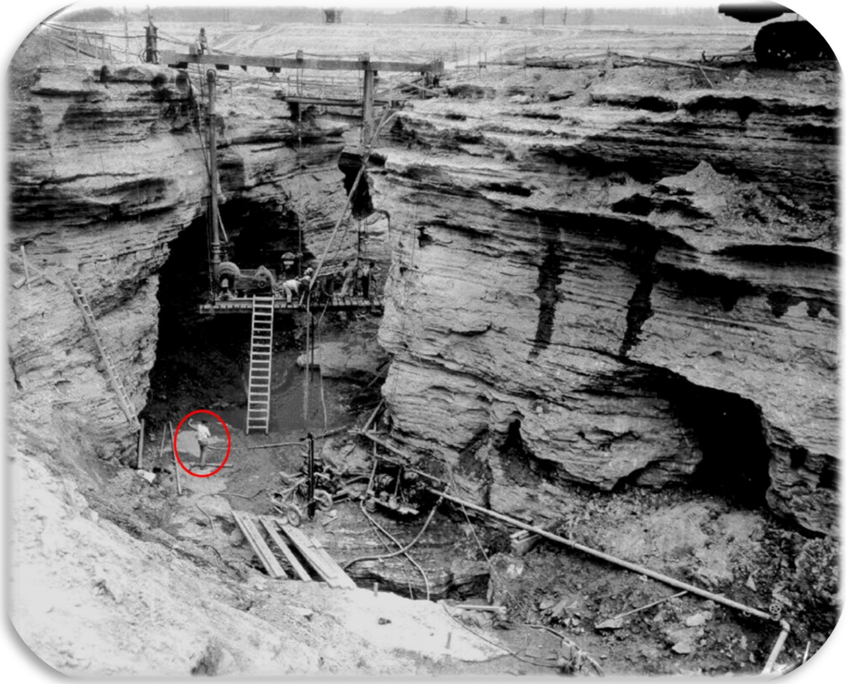

Beaver Major Rehabilitation
Dike 1
Cutoff Wall Construction Area

W.F. George, AL

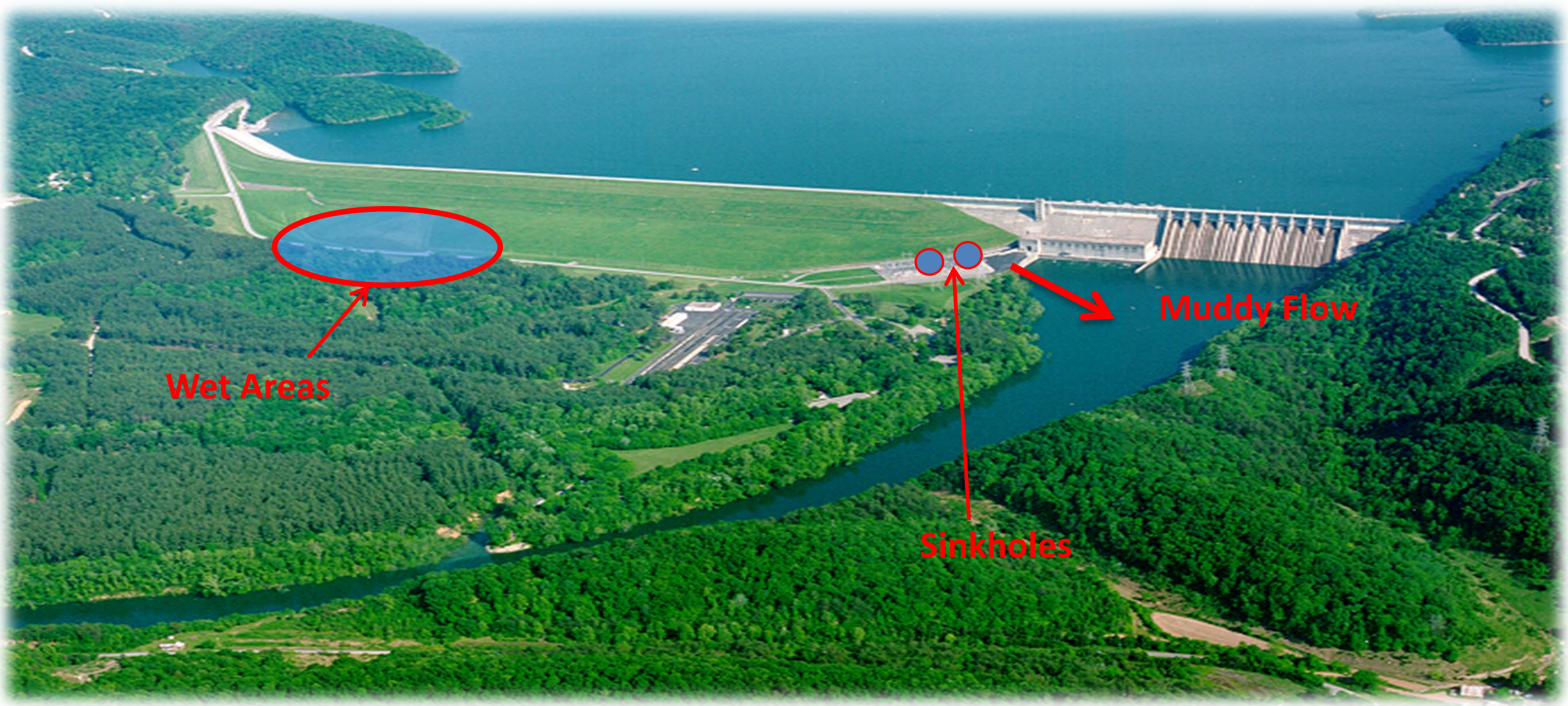
3. CUTOFF WALLS FOR DAMS

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.

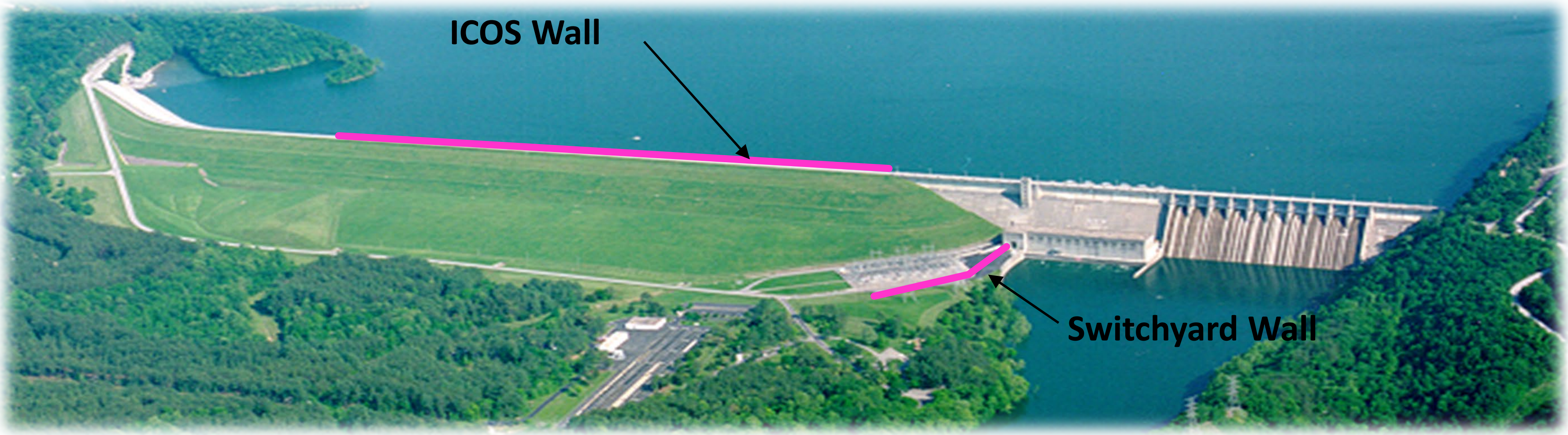


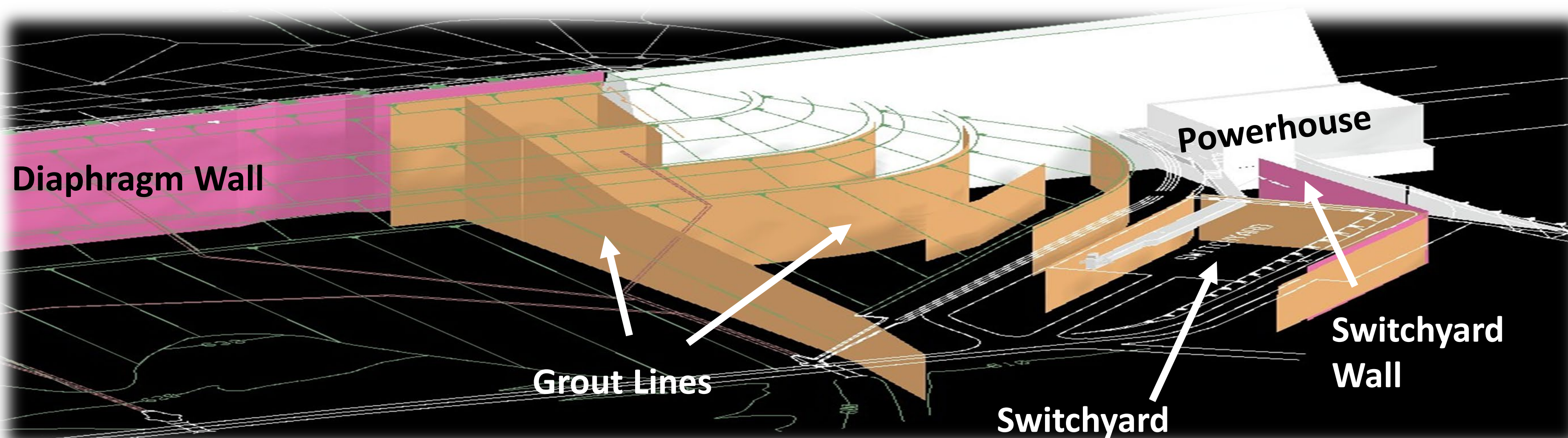
- Designed in the 1930's, built from 1941-1943 and 1945-1952.
- Severe hydraulic distress observed after impoundment leading to emergency grouting by USACE in 1968-1970 and 1973-1975.



- 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





First Solution – Cutoff Wall and Extensive Grouting Campaigns

ICOS' barrier wall was installed along the centerline of the Embankment

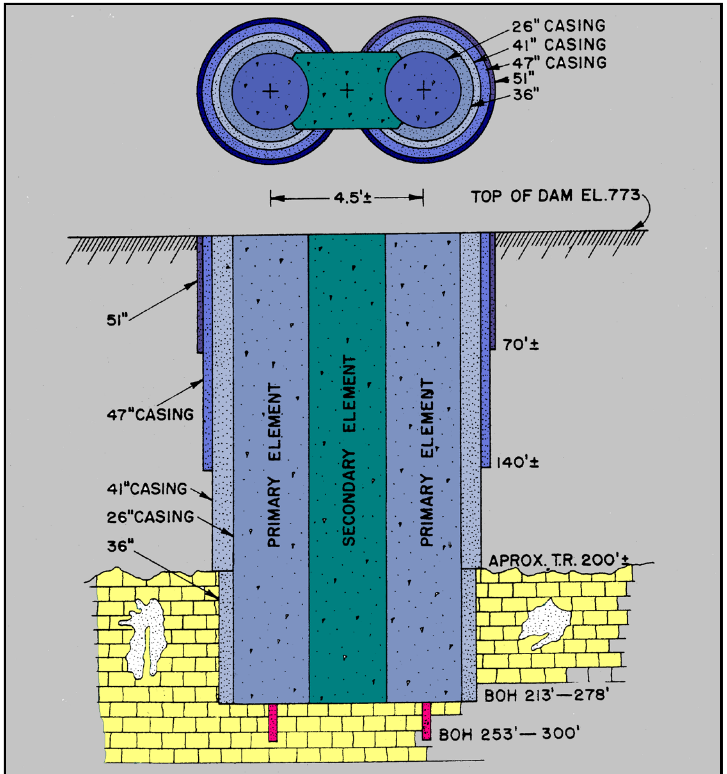


FIG.3 TYPICAL SECTION OF COMPLETED DIAPHRAGM WALL.

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.

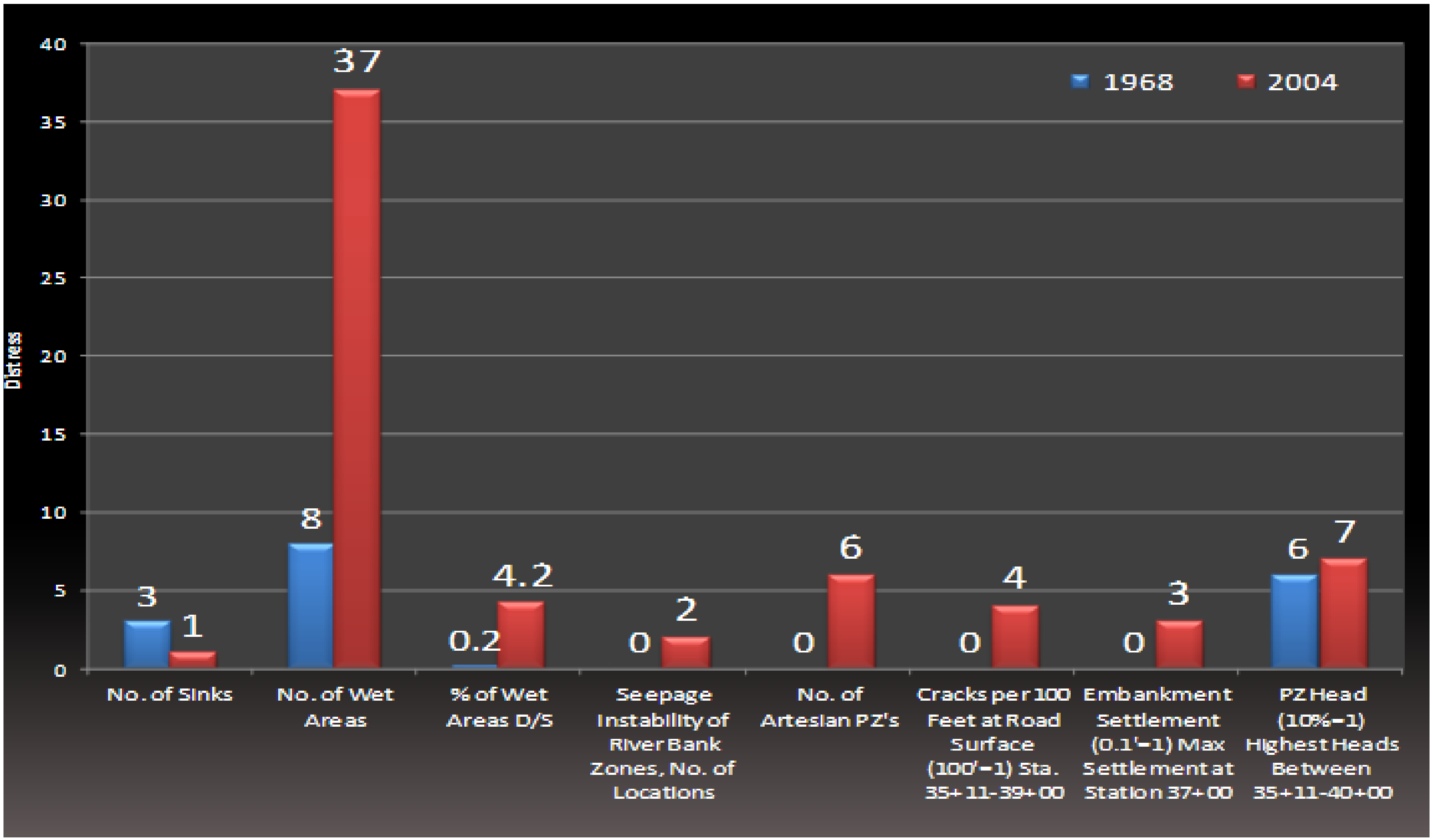
HOWEVER…

- 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.

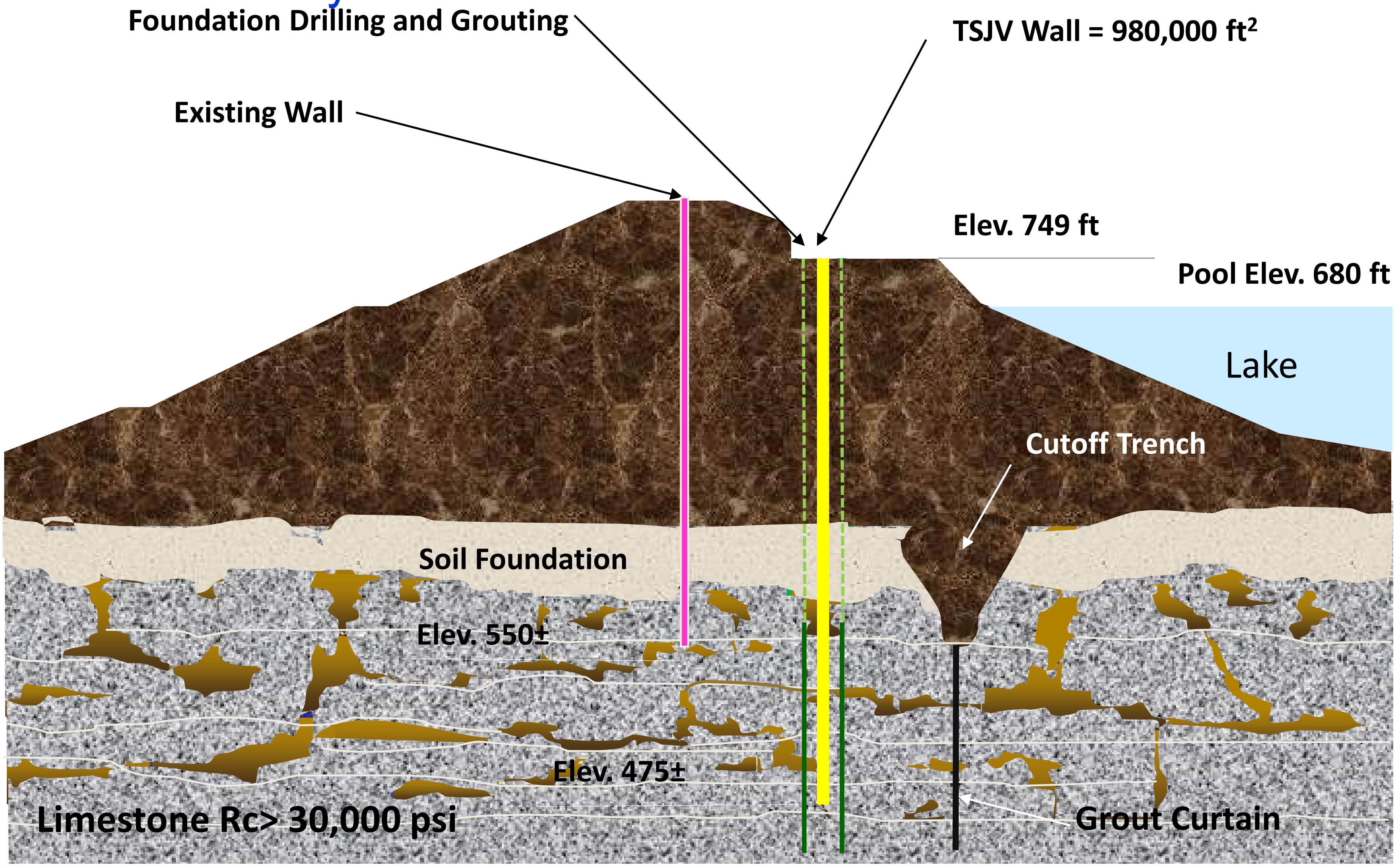
- By January, 2007, Wolf Creek Dam was judged to merit a DSAC-1 rating – therefore requiring urgent and compelling action. The justification was a return of the classic distress symptoms.

Increasing Distress Indicators



- 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.

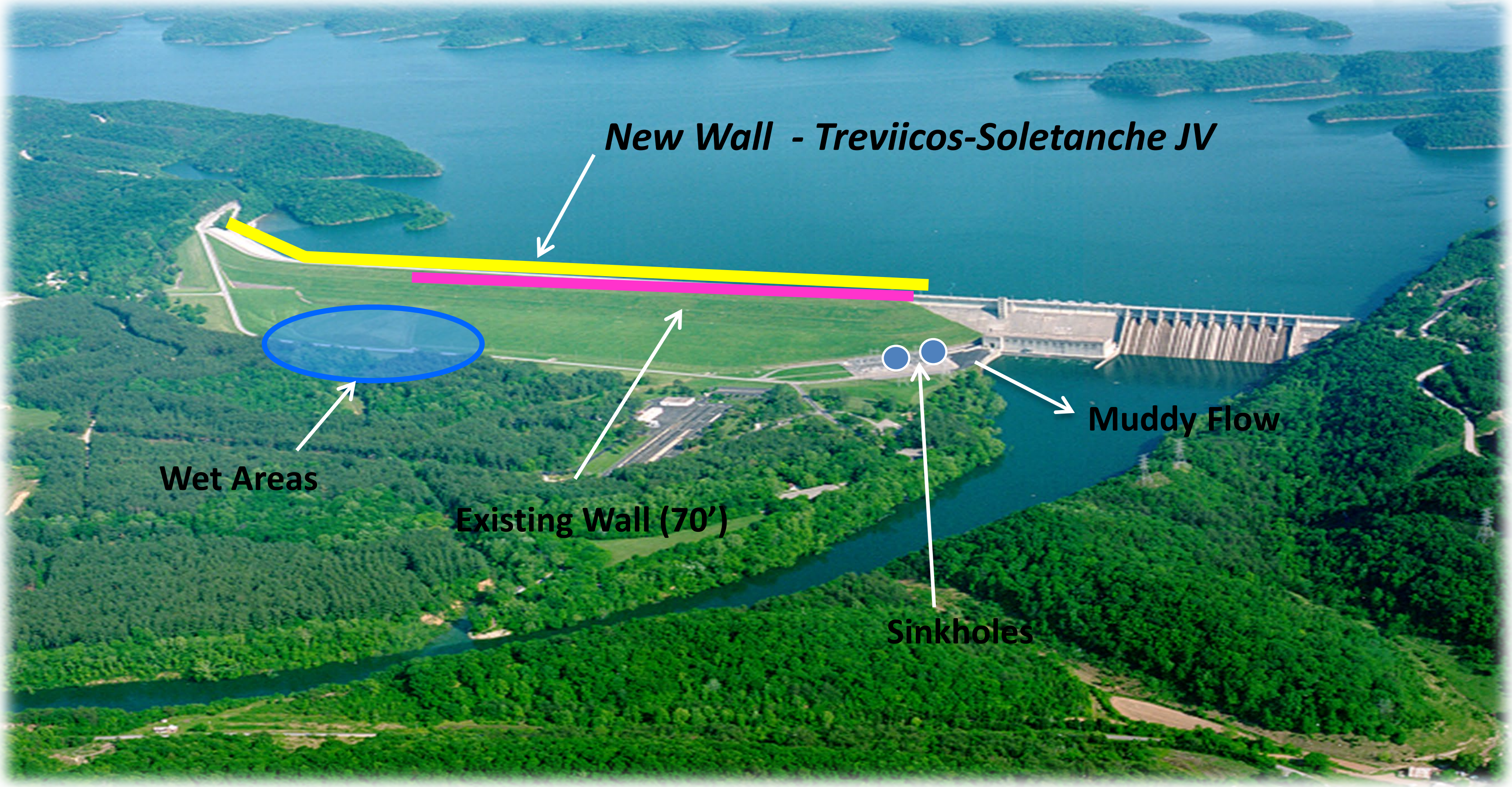
The Solution by USACE



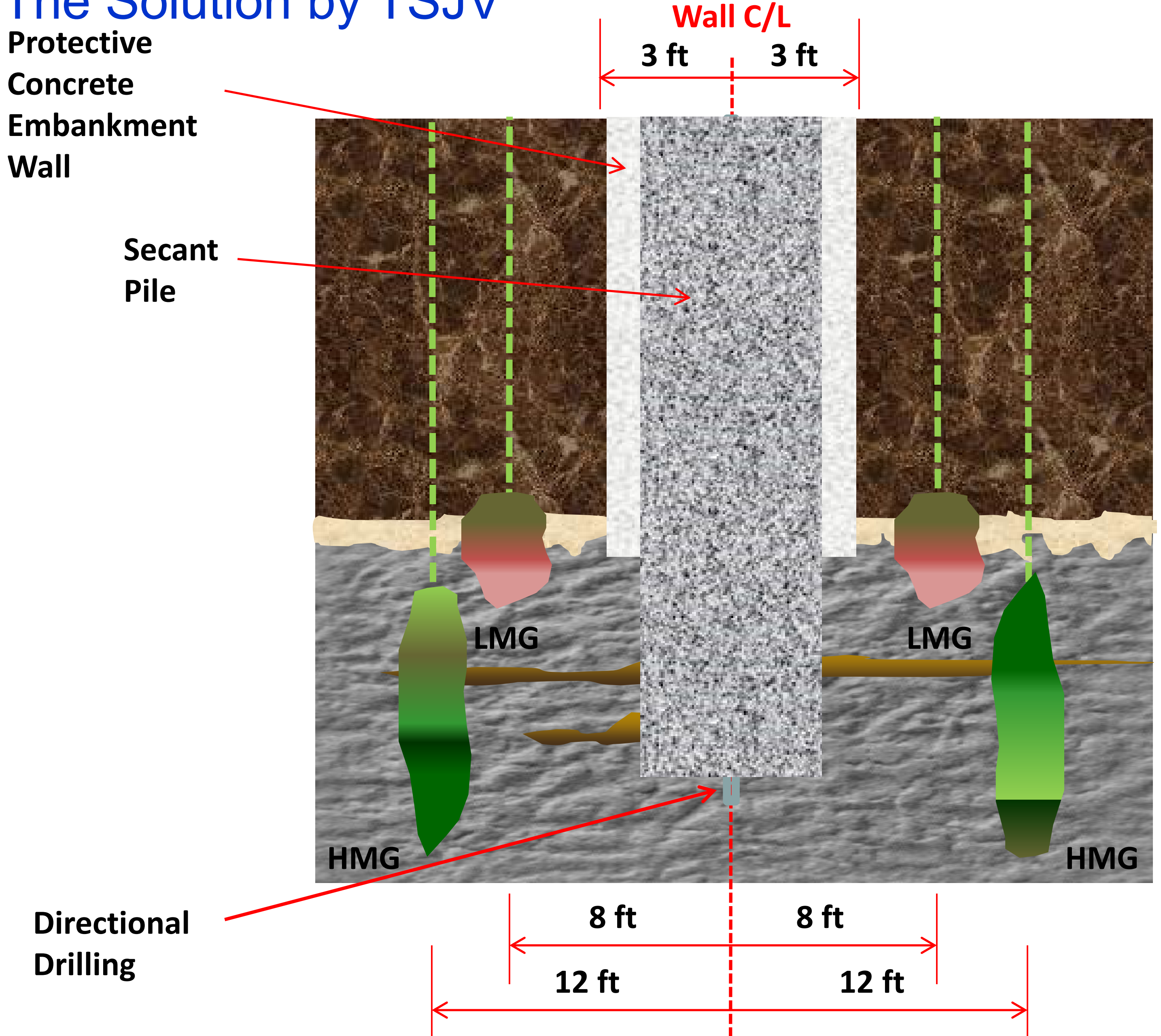
3.2 Availability of the Technology

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



Strength between 10,000 and 36,000 psi

Festures up to 40 ft in height

Mixed rock/soil conditions

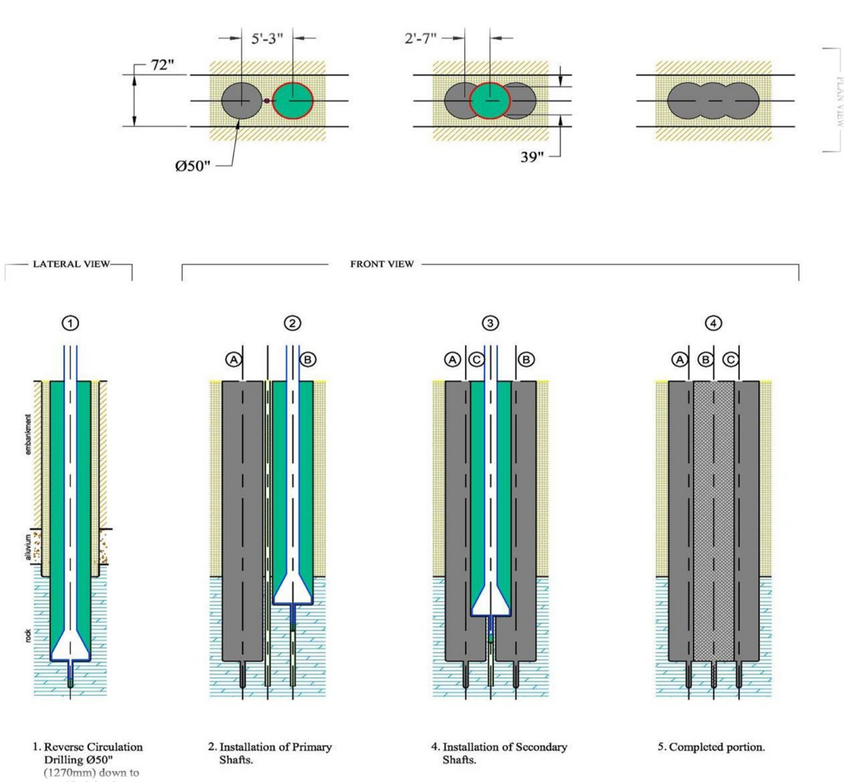
- Hayward Baker were engaged to explore and pretreat the potentially vulnerable embankment/rock contact with a LMG operation, and to thereafter extend the Advanced/Gannett Fleming grout curtain.

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



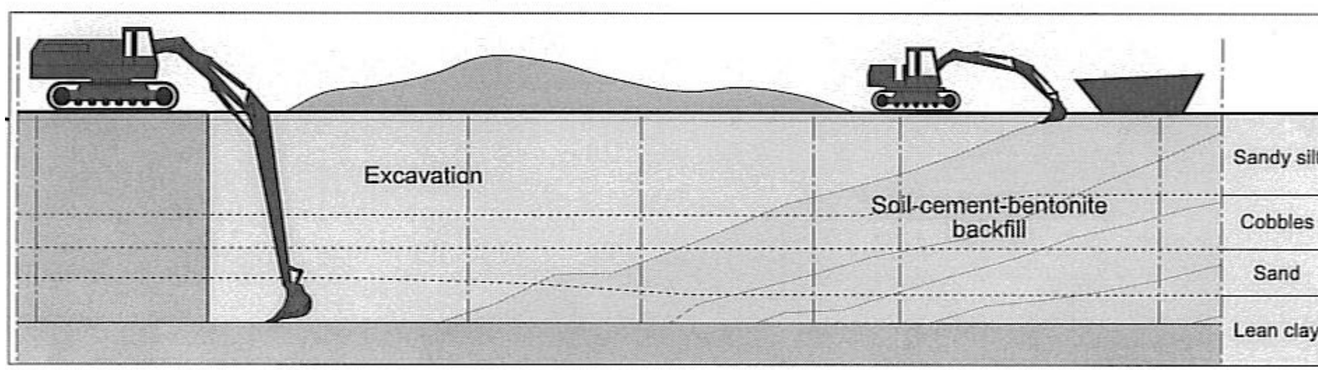
Secant Pile Method "Arapuni"

Field Trial, Rome, Italy

Field Trial, Rome, Italy

First test panel, Arapuni, NZ

- Excavation Principles
  Continuous Wall (Backhoe)



Typical cross section

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.

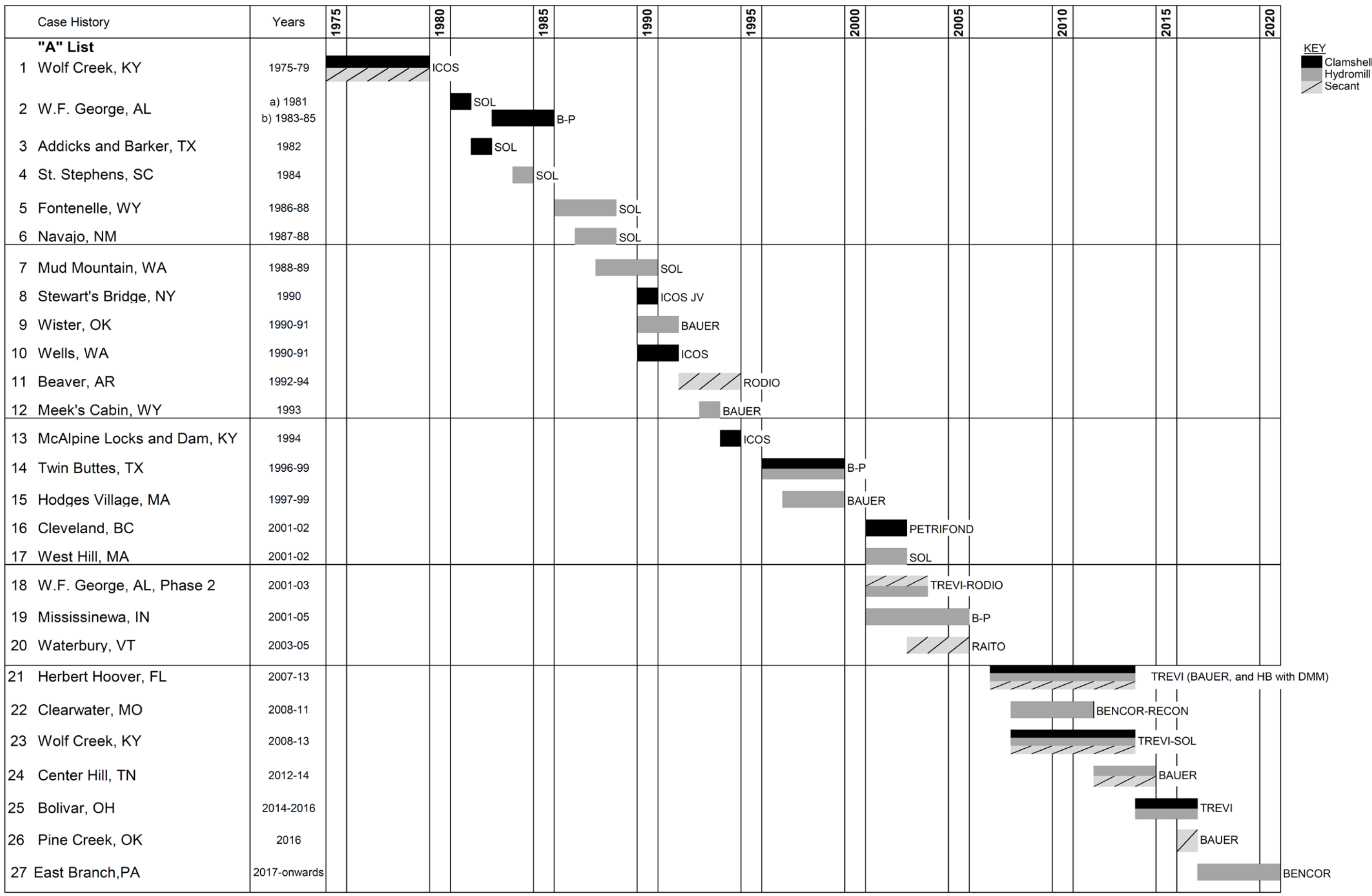
- Clamshell and hydromill operations need substantial working platform, guidewalls, slurry plants, etc.
- Hydromill walls are typically non-competitive except where special conditions exist (e.g., very hard layers, boulders, etc.).

U.S. Case Histories – 1975-2016

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
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 to 2016



B-P = Bencor-Petrifond
BAUER = Bauer Spezialteifbau GmbH
HB = Hayward Baker
ICOS = TreviICOS

PETRIFOND = Petrifond
RAITO = Raito
RECON = Remedial Construction Services

RODIO = Rodio
SOL = Soletanche
TREVI = TREVIICOS

Category 1 Concrete Cut-Offs for Existing Embankment Dams (1975-2005)

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**

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
  - Wet End Mix
  - Wet Shaft Mix
  - Dry End Mix
- Jet Assisted Vertical Axis (Turbojet)
- Continuous Trench Cutting
  - TRD
  - "One Pass"
- Horizontal Axis Cutting and Mixing
  - Low Pressure (CSM)
  - High Pressure (CT Jet)

"Conventional"

Conditions Favoring DMM

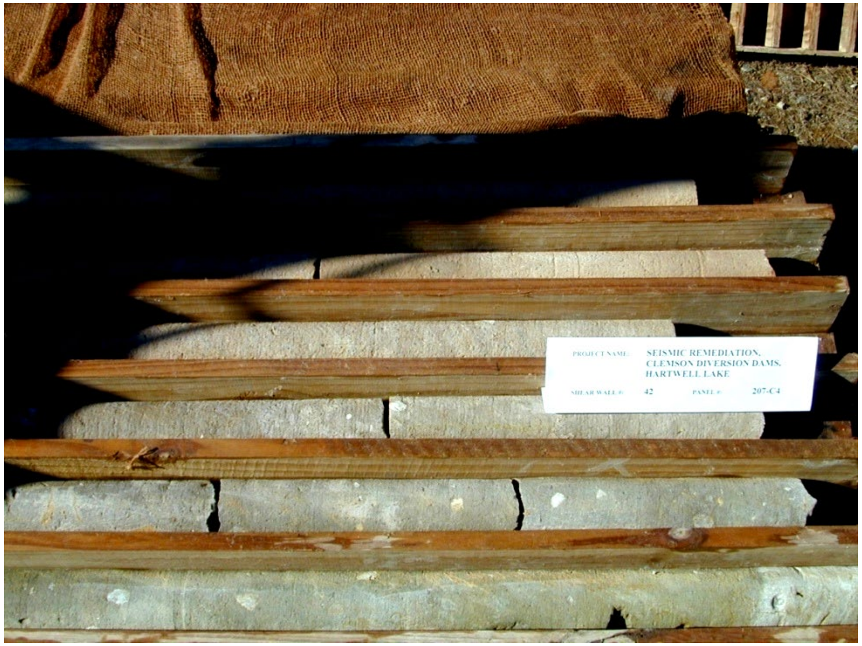
- Ground is neither very stiff or very dense
- Ground has no boulders/obstructions
- Treatment < 40 m depth
- Unrestricted overhead clearance
- Good and constant binder source
- Large spoil volumes can be tolerated
- Vibrations are to be avoided
- Treated soil volumes are large
- “Performance Specifications”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


NITTOC

“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.



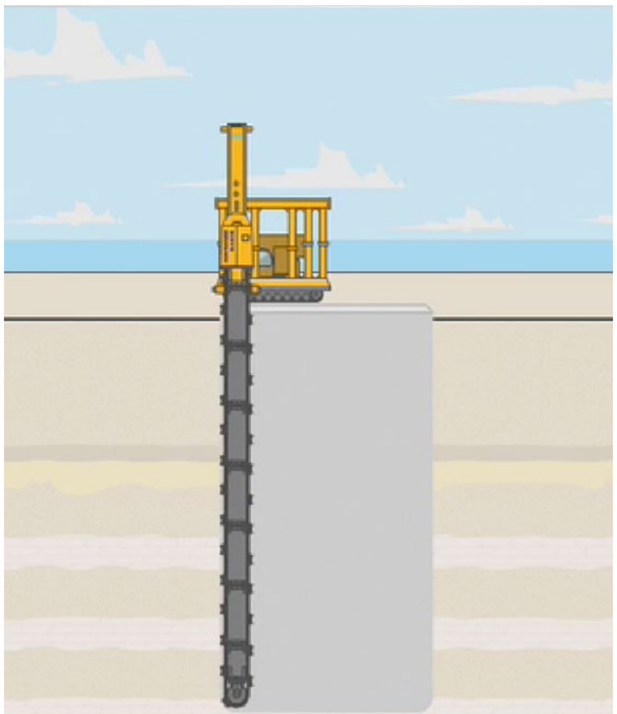
“Conventional” DMM

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

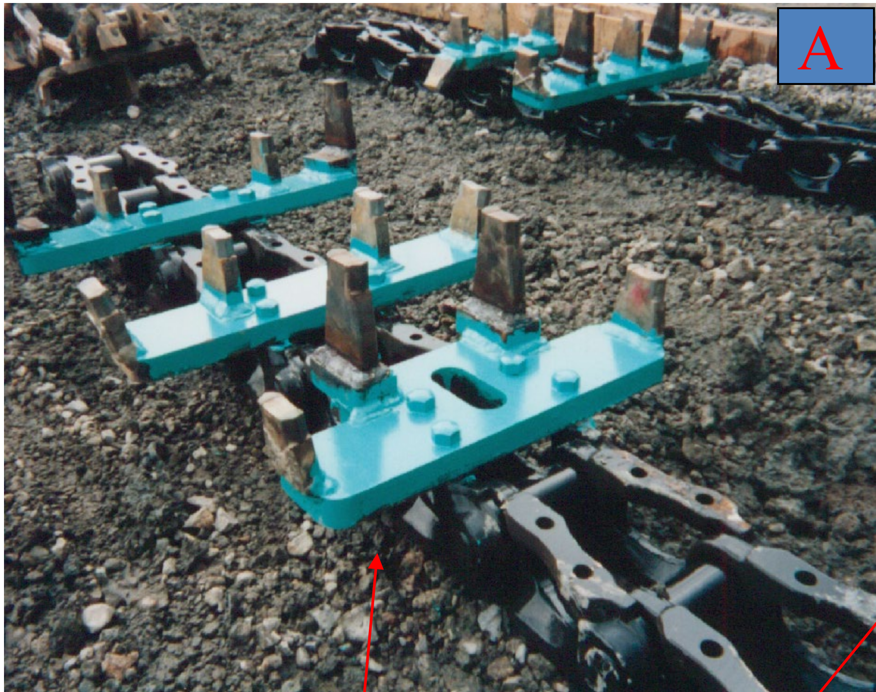
TRD (Trench Re-Mixing and Cutting Deep Wall) Method

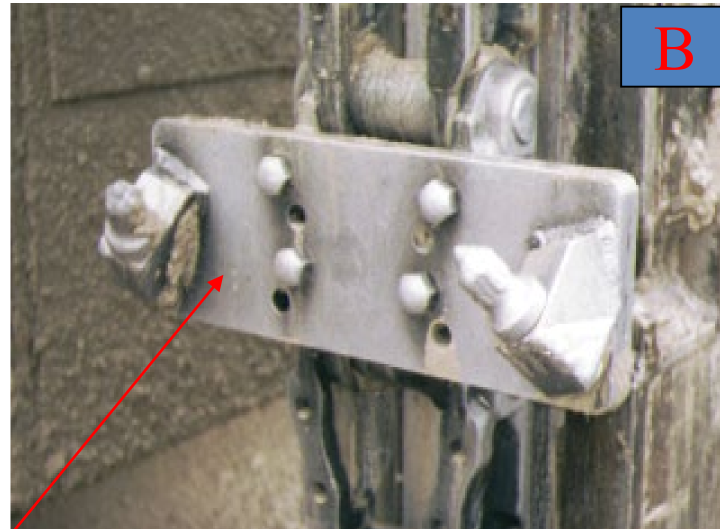


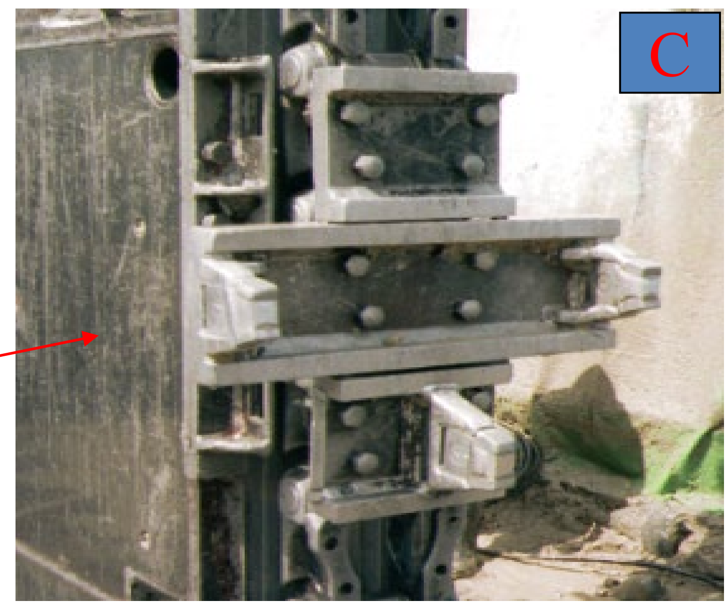
- Conceived in 1993 in Japan.
- First used in U.S. in 2005.
- 170 ft. depth capability, 18-34 inches wide.
- Continuous wall created by lateral motion of vertical "chain saw," installed in a predrilled hole.

Blue print

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 conzditions.
- 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

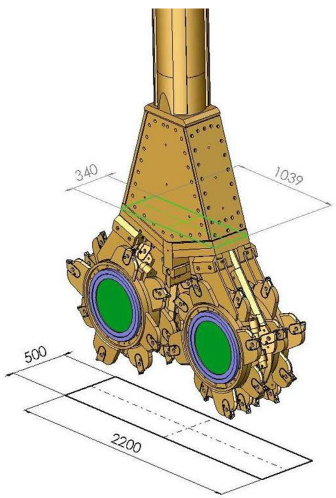
- Sharp alignment changes.
- Especially hard/massive/abrasive rock.
- Trapping of “post” in soilcrete or “refusal” on boulders/rock.
- Only one (excellent) contractor!

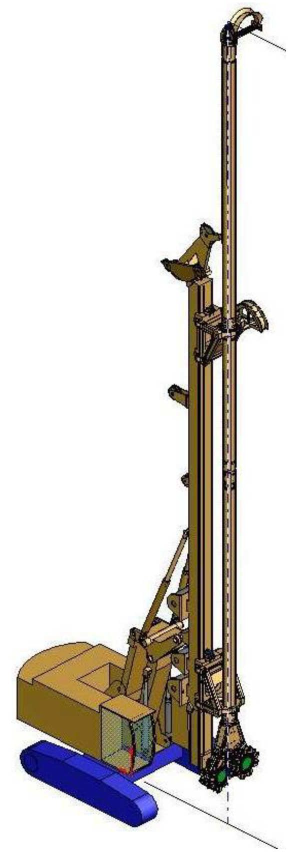
"One Pass" System (DeWind)


KOBELCO
ONE-PASS TRENCHING
MT-3500 DEWIND ONE-PASS TRENCHING


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.





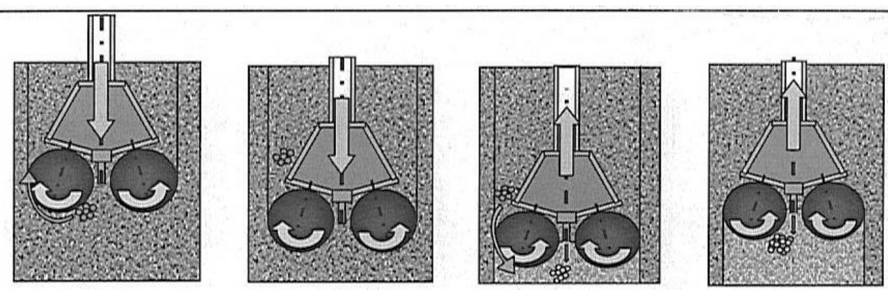


Diagram showing the CSM process

CSM Quality Control Systems

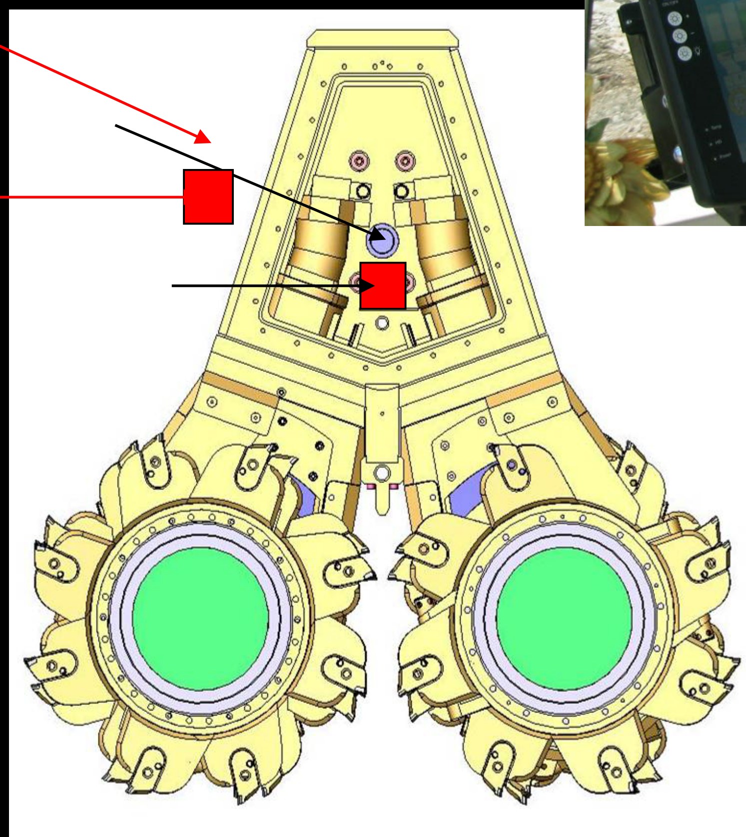
The CSM machine is fitted with a set of instruments that convey to the operator, in real time, all the information that is needed to monitor and control quality of the work.

BAUER B-Tronic system

External pressure sensor

Instruments that read:

- Verticality on "X" and "Y" axes
- Torque on cutting wheels
- Wheel speeds



WILLIAMS
EARTH SCIENCES
Choose Integrity
USDOT1213 19
F SERIES
PANEL:
1509132
DATE: 3-19-09
Depth: 20-25FT
TOP
BOT

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

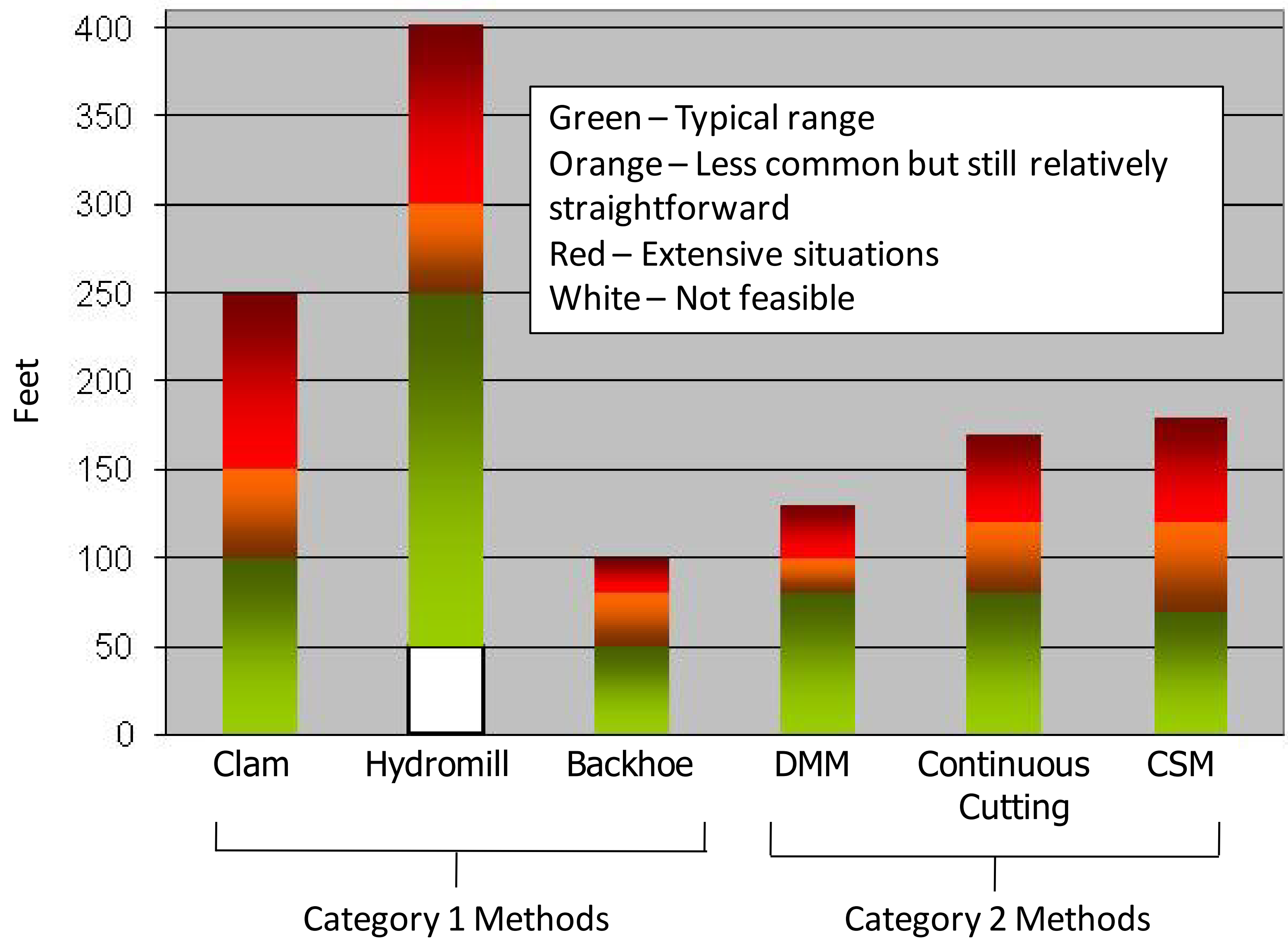
METHOD	PRINCIPLE	WALL DIMENSIONS		PROPERTIES OF BACKFILL		COSTS		RELATIVE BENEFITS/PROBLEMS	
		DEPTH	WIDTH	UCS	K	MOB/DEMOB	UNIT PROD.	PROS	CONS
Category 1 – Excavate and Replace (i.e., under bentonite slurry)									
Clamshell	Various types of clams can be used to remove soil in panels	Max 250' (typically < 150')	16-66" (typically 24-36")	Wide range of materials can be used for backfill depending on project requirements		Low-Moderate	Moderate-High	• Experience • Adaptability • Wide range of backfills • Considerable depth capability	• Spoils handling • Boulders • Rock • Verticality control • Loss of slurry • Access/headroom
Hydromill	Large frame with cutting wheels and reverse circulation mud pump to remove soil in panels	Max over 400'	24-60" (typically 33-39")	Wide range of materials can be used for backfill depending on project requirements		Moderate-Very High	High-Very High	• Greater depth capability • Can penetrate all conditions • Can be very fast • Verticality control	• Cost base • Loss of slurry during excavation • Spoils handling • Access/headroom
Backhoe	Modified long reach excavator to create continuous trench	Max 100' (typically < 80')	30-36"	Mainly used with SB backfill, but feasible with SCB and CB		Very Low	Very Low	• Very high productivity • Low cost • Experience • Many practitioners • Practical in tight access/low headroom conditions	• Depth limitation • QA/QC • Obstructions/ dense or stiff soil/rock
Category 2 – Mix in Place									
Conventional DMM	Vertically mounted shafts are rotated into the soil creating panels of soilcrete	Maximum practical about 110'	20-40"	100-1,500 psi	5×10^{-6} to 1×10^{-8} cm/s	Moderate-High	Low to Moderate	• Speed • Experience • Several practitioners • High productivity	• Large equipment needs good access and virtually unlimited headroom • Depth limits • Very sensitive to obstructions • Variable homogeneity with depth • Cost base

(continues)

Method	Principle	Wall Dimensions		Properties of Backfill		Costs		Relative Benefits/Problems	
		Depth	Width	UCS	K	Mob/Demob	Unit Prod.	Pros	Cons
TRD	Vertical chainsaw providing simultaneous cutting and mixing of soil to produce continuous soilcrete wall	Maximum 170'	18-34"	100-3,000 psi	10^{-6} to 10^{-8} cm/s	Moderate-Very High	Moderate-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	• Difficult wall geometries • Medium-hard rock, and boulder nests • Currently only one U.S. contractor • Requires very specialized equipment • Cost base
CSM	Cutting and mixing wheels mounted on horizontal axes create vertical soilcrete panels	Max 180' (Deeper and wider with CT Jet variant)	20-47"	100-3,000 psi	10^{-6} to 10^{-8} cm/s	Low-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	• Rock, boulders and other obstructions • Cost base

Key to Costs

Mob/Demob		Unit Costs (i.e., cost per square foot of cut-off)	
< \$50,000	Very Low	< \$10	Very Low
\$50,000-\$150,000	Low	\$10-\$20	Low
\$150,000-\$300,000	Moderate	\$20-\$50	Moderate
\$300,000-\$500,000	High	\$50-\$100	High
> \$500,000	Very high	> \$100	Very High



Feet
0
50
100
150
200
250
300
350
400
Green – Typical range
Orange – Less common but still relatively straightforward
Red – Extensive situations
White – Not feasible
Clam
Hydromill
Backhoe
DMM
Continuous Cutting
CSM
Category 1 Methods
Category 2 Methods

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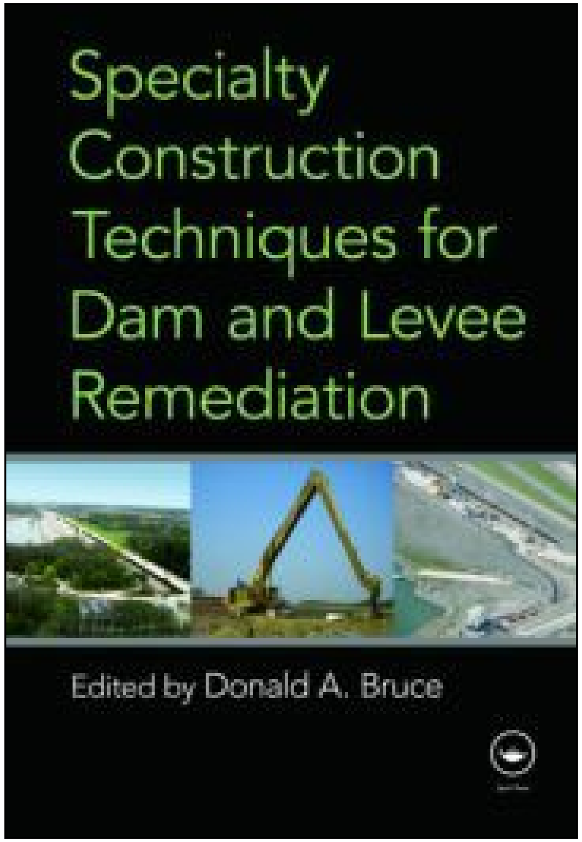
USACE

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