

The Deep Mixing Methods



May 2022

1

Agenda

1. In the Beginning
2. Some Landmark Projects and Events
3. New Arrivals



May 2022

2

1. IN THE BEGINNING

1954	Original MIP System (Intrusion Prepack)
1986	SMW Seiko arrive in U.S.
Late 1980's	Jackson Lake Dam, WY (Seiko/GeoCon)
Late 1980's	Start of Environmental Applications (GeoCon)
Early 1990's	Start of Levee (Cutoffs) and Dam (Seismic) Remediations
1992-1994	First major Earth Retaining Structure (Boston, MA)
1995	Visit by U.S. engineers to Japan
1996	First Lime-Cement Column project (New York)
1997-1998	Largest wet DMM project to that time (Boston, MA)
1997-2000	FHWA State of Practice Studies are published
Early 2000's	Technical Exchanges with Japan

May 2022

3

IN THE BEGINNING (continued)

2000-2003	Desk, Bench and Field Tests, New Orleans
2001-2005	National Deep Mixing Research Program (States Funded)
2003	International Conference in New Orleans
2005	Katrina and Rita
2006	Task Force Guardian
2006	CSM brought to Canada and TRD brought to U.S.
2006-2007	Deep Mixing at Tuttle Creek Dam, KS
2007-Present	National Deep Mixing Project Revised
2008-Present	Cutoff Walls at Lake Okeechobee
2010-2011	LPV 111, New Orleans, LA
2012	International Conference in New Orleans
2012-2013	Kitimat, BC
2013	Increasing DFI support for DMM
2015	USACE, Reclamation and DFI Manuals

May 2022

4

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



May 2022

5

Jackson Lake Dam modification (1987 – 1988)



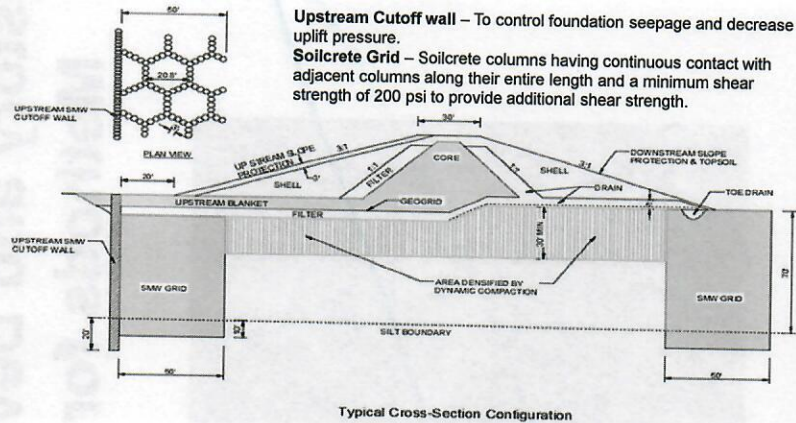
Source: Bureau of Reclamation web site
DM cells were installed using equipment of
SMW Seiko, Inc. in 1987 and 1988.

- A 49-ft hydraulic fill dam; 4,300 ft long northern embankment founded on fluvial-lacustrine and lacustrine sediments
- Northern embankment and foundation were found to be susceptible to earthquake induced liquefaction by Seed & Lee in 1977.
- The primary objective of the construction program was to modify the structure and foundation to preclude failure due to the design earthquake
- Modifications to provide earthquake stability included:
 - Replacement of the Northern Embankment
 - Foundation treatment

May 2022

6

Foundation stabilization of Jackson Lake Dam



Sources: 1. Foundation Stabilization of Jackson Lake Dam, A. Pujol-Rius, P. Griggin, J. Neal and O. Taki, 12 International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, August 1989; 2. Foundation Treatment Methods for Jackson Lake Dam Modification, J. Farrar, K. Wirkus & J. McClain, USCOLD

Courtesy
of JAFEC
USA, Inc.

May 2022

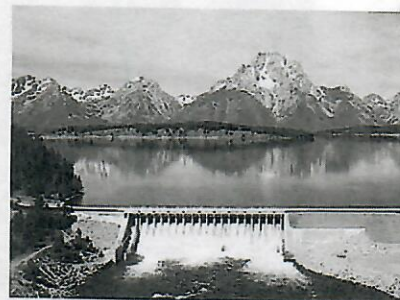
7

DM design concept



"We are using soilcrete columns to increase the shear strength of the foundation." 1987

Source: Jackson Lake Dam project boasts unusual soil-improvement method, Intermountain Contractor, Oct 1987



"...To the right of station 29+00 the SMW structure designed to prevent liquefaction of soils both the upstream and downstream outer shells of the embankment is in place." 2004

Source: Bureau of Reclamation Technical Memo. No. JL-8313-4 Issues Evaluation Report of Findings-Executive Summary Seismic Risk Analysis, 2004

May 2022

8

**First Multiple Auger
Drill Manufactured in
U.S.
Hialeah, FL (~1988)**



May 2022

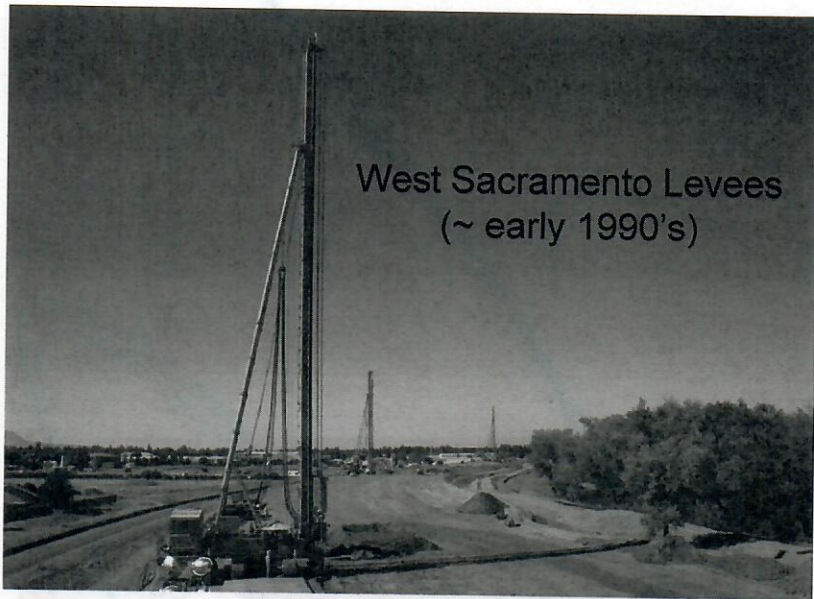
9



**First Large-Scale SSM
Project (~1989)**

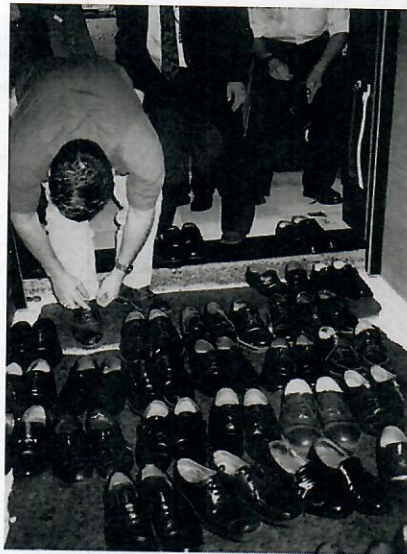
May 2022

10



May 2022

11



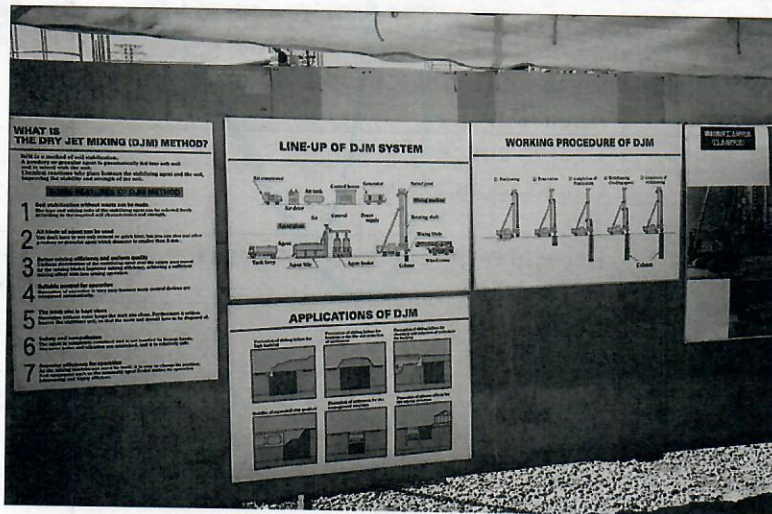
May 2022

12



May 2022

13



May 2022

14



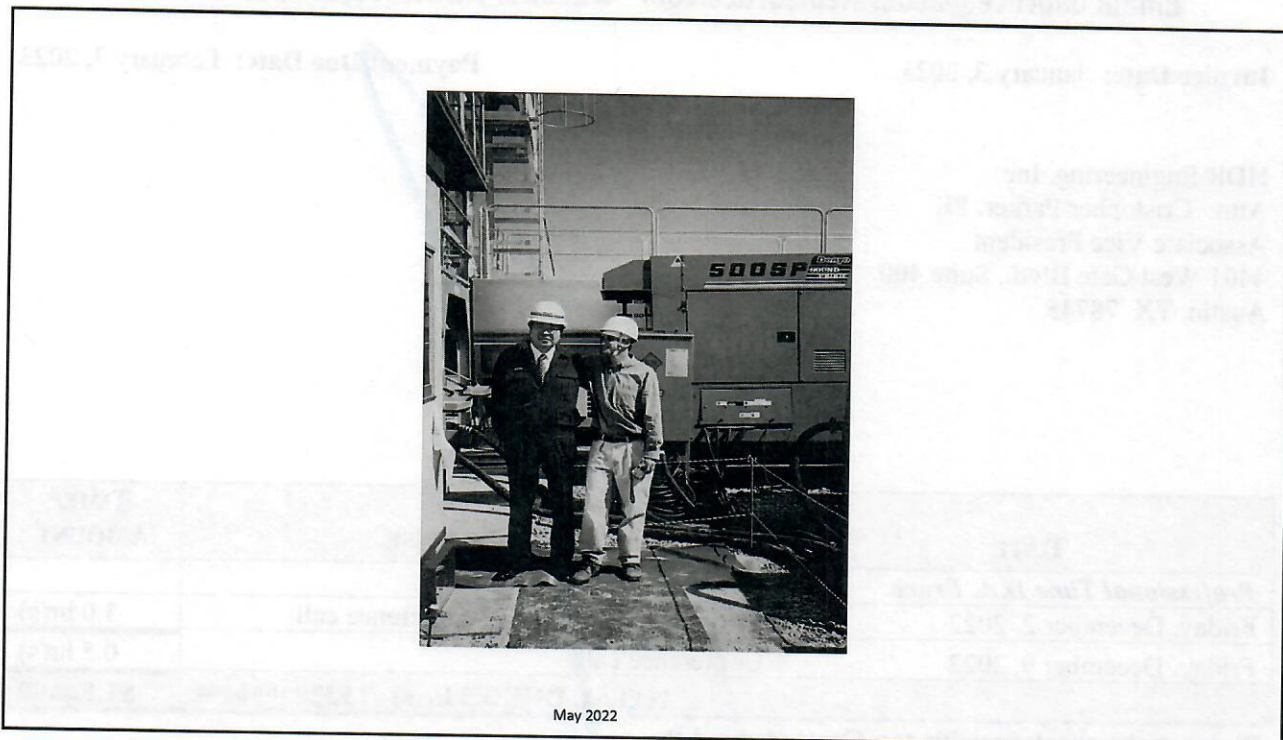
May 2022

15



May 2022

16



May 2022

17



May 2022

18



May 2022

19

2. FOUR LANDMARK PROJECTS

Caveats and Apologies

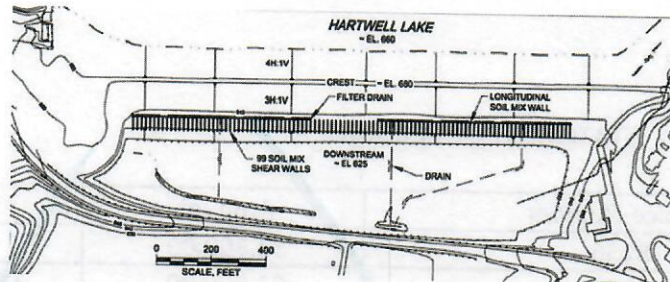
- Incomplete (e.g., important DMM projects conducted in Bay Area, the Pacific Northwest, and on California Dams and Levees)
- No contractor preference implied, but:
- Thanks for all the contractors who sent images – including: Bauer Foundations; DeWind, Fudo, GeoSolutions/GeoCon, Golder Construction, Hayward Baker, Jafee, Malcolm, Nicholson, Raito, Schnabel Foundations, TREVIICOS, Underpinning and Foundations
- Special thanks to Dr. David Yang of Jafec USA Ltd., Gilbert Tallard, Dr. Pete Cali, and Prof. George Filz



May 2022

20

2.1. Clemson Upper & Lower Diversion Dams South Carolina



- The foundation soils of the 80-ft high dam consist of a loose silty sand / sandy silt alluvial deposit with thickness varying from 7 to 28 ft.
- Seismic investigation and evaluation concluded that there was a potential for a liquefaction-induced slide of the downstream slope during the design seismic event due to low estimated values of steady-state undrained strength at large strain in the foundation alluvial soils.

Sources: 1. "Evaluation and Design of Seismic Remediation for the Clemson Upper and Lower Diversion Dams," Wooten, R. L., Castro, G., Gregory, G., and Foreman, B., Proceedings of the 23rd Annual United States Society on Dams Conference, 2003. 2. "Deep Soil Mixing for Seismic Remediation of the Clemson Upper and Lower Diversion Dams," Wooten, R. L., and Foreman, B., Proceedings of the 25th Annual United States Society on Dams Conference, 2005

May 2022

21

Clemson Upper & Lower Diversion Dam South Carolina

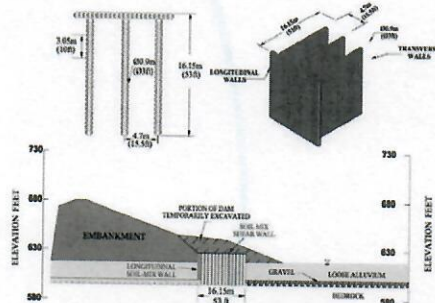


Fig. 7. Cross Section and Layout Design, Seismic Remediation of Clemson Upper and Lower Diversion Dams (base by Wooten & Foreman, 2005)

DM transverse shear walls - Oriented perpendicular to the dam axis to carry the seismic loads in lieu of the weak soil layers.

DM longitudinal wall - To prevent softened alluvium from squeezing or flowing between the transverse walls.

DM walls installed by Raito, Inc. in 2004 & 2005

Source: Application of Multi-shaft Deep Mixing in the U.S., David S. Yang, *National/Regional Reports, Deep Mixing 2009 Okinawa Symposium, Okinawa, Japan, May 2009*

May 2022

22



May 2022

23

2.2. Deep Mixing in New Orleans

1. Phase 1: First Demonstration Program (2001)
2. Phase 2: Task Force Guardian and Beyond (2006-2010)
3. Phase 3: LPV 111 and others (2009 onwards)



May 2022

24

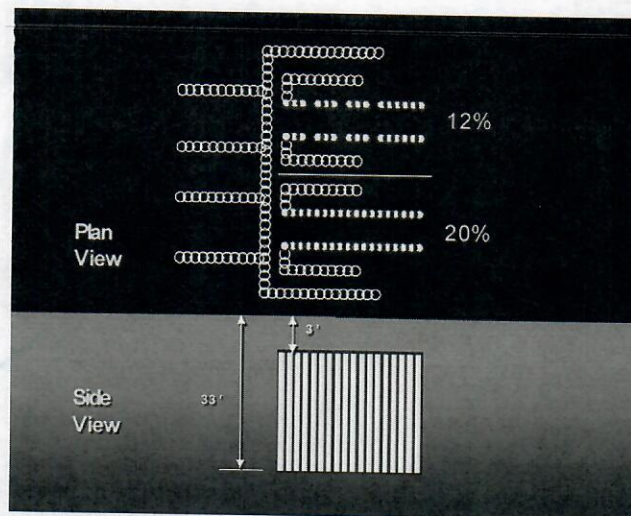
Phase 1: First Demonstration Program (2001)

- No prior history of DMM in the area despite very poor soils and huge levee infrastructure.
- Usual reasons can be cited:
 - Reliance on “traditional” solutions.
 - Lack of funds.
 - “There must be a problem before there is a solution.”
- USACE raised funds for a classic “3 step” research program:
 - Desk study (feasibility in local soils).
 - Lab study (properties of mixed soils).
 - Full-scale field test (performance of columns at different replacement ratios).



May 2022

25



As-built cell configuration with 12% and 20% replacement ratios.

May 2022

26



Extraction of Top of Column

May 2022

27



Cell A fully loaded with 1100 tons of steel

May 2022

28

Outcome of Test Program

Invaluable information was gained on designing and constructing Deep Mixing in the local soils. However, there remained some doubts (misunderstandings) in certain quarters about its technical and commercial viability in Louisiana and so it was decided to keep DMM "on ice."



May 2022

29

Phase 2: Task Force Guardian and Beyond (2006-2010)

- August 2005 Hurricanes Katrina and Rita force the "ice" to melt.
- Contents of an email from Dr. Pete Cali to a DMM colleague in Scandinavia, Friday, September 16, 2005:

"Dear ____, Thank you for your concern. We are OK. Lots of property damage, but all are well. When we get to the other side of this emergency, raising the height of the levees will be a priority, and hopefully deep mixing will play an integral role" (underline added).



May 2022

30

Four Task Force Gardian Projects (2006)

- ❖ Orleans Avenue Interim Closure Structure
- ❖ 17th Street Canal Interim Closure Structure
- ❖ Homeplace Levee Enlargement
- ❖ Gainard Woods Pump Station



May 2022

31

Phase 2: Wet Mixing at Orleans Avenue



May 2022

32

Phase 2: Dry Mixing at 17th Street Canal and Homeplace Levee



May 2022

33

Phase 2 Projects (Task Force Guardian to 2010)

PROJECT NAME	START DATE	APPLICATION	DETAILS	CONTRACTOR
17 th Street Canal	2006	Overwater mixing for interim canal closure structure in cellular grid pattern.	2,200 DRE columns, 800 mm diameter, 18 m deep	Hayward Baker, Inc.
Orleans Avenue Canal	2006	Overwater mixing for interim canal closure in rows and "hammer heads."	Triple axis WRE in rows and square grid. About 6,000 cubic meters of treated soils.	Raito, Inc.
Gainard Woods Pump Station	2006	Emergency levee repair.	Triple axis WRE.	Raito, Inc.
P24 Plaquemines Parish	2006	Foundation stabilization with rows of columns for levee raising.	4,600 DRE columns, 800 mm diameter, 13 m deep	Hayward Baker, Inc.
Westwego Interim Phase 1	2008	Flood wall replacement.	Triple axis WRE.	Raito, Inc.
Westminster Pump Station	2008	Ground improvement for new structure in cellular grid.	DRE columns, 800 mm diameter	Hayward Baker, Inc.
Westwego Pump Station Phase 2	2009	T-wall foundation stabilization.	Triple axis WRE	Raito, Inc.
IHNC Reach III	2010	Soil improvement under I-wall levee section in panels.	DRE columns, 800 mm diameter 11.6 m deep	Hayward Baker, Inc.
LPV-109.02	2010	Levee raising.	Triple axis WRE	Raito, Inc.
WBV-09a	2010	First levee enlargement and pump station	Triple axis WRE	Raito, Inc.
WBV47.1	2010	Levee Raise	DRE Columns	Hayward Baker, Inc.

May 2022

34

Phase 3: LPV 111 (2010-2011)

- Lake Pontchartrain and Vicinity Hurricane Protection System Contract 111 extended over 6 miles along the north bank of the Gulf Intracoastal Waterway (GIWW).
- Bordered on both sides by the Bayou Sauvage National Wildlife Refuge.
- Levee raising therefore restricted to existing right of way and hence DMM was the cost effective solution for foundation soils.



May 2022

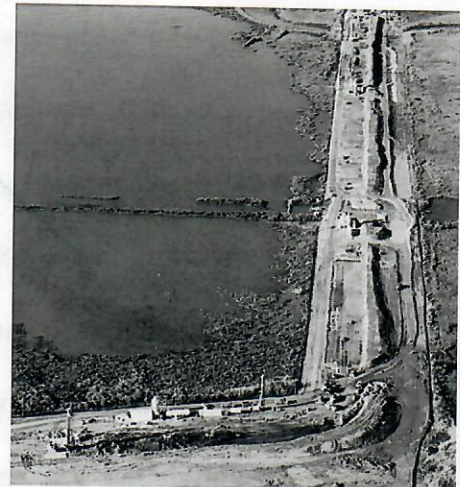
35

Construction

LPV111 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 $\rightarrow$ 17,500 trucks
- 3 coring rigs
- over 500,000 man-hours in 14 months of production



May 2022

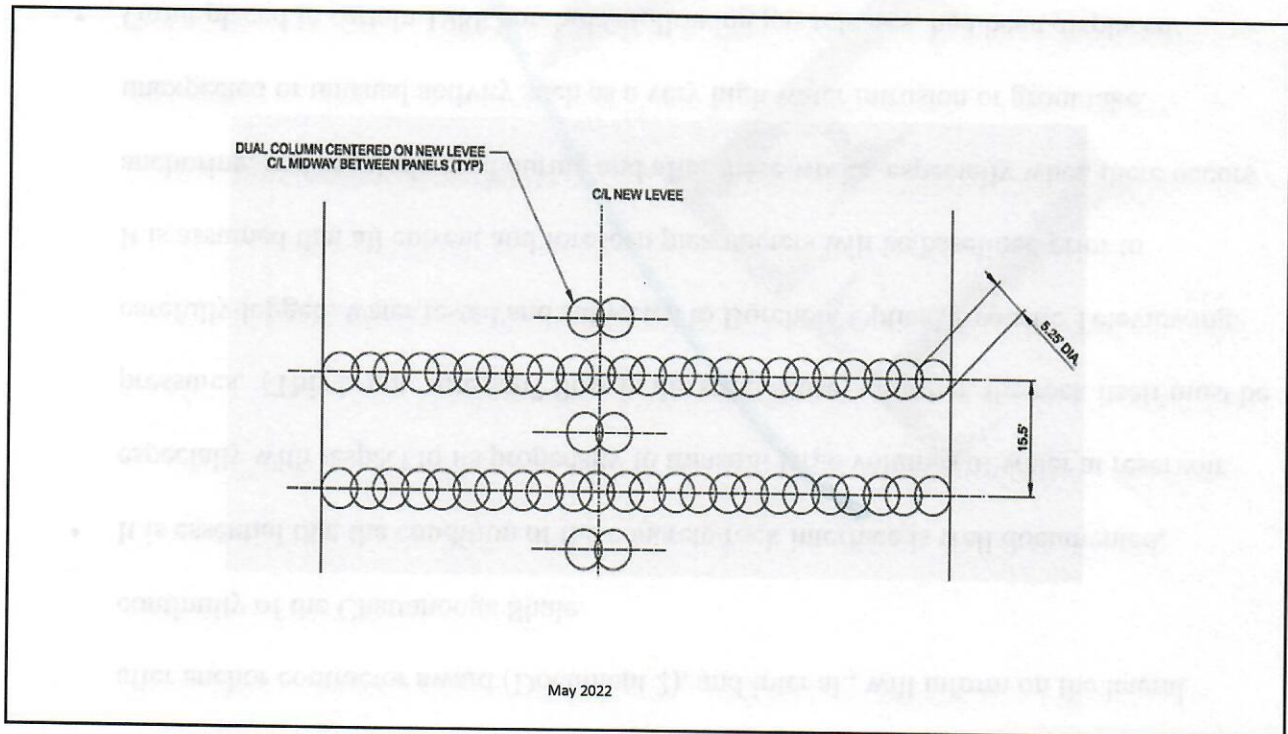
36

LPV III Production

PRODUCTION START DATE		1/14/2010
PRODUCTION COMPLETION DATE		3/18/2011
TOTAL CALENDAR DAYS	N	439.00
TOTAL MONTHS	N	14.43
TOTAL SHIFTS WORKED (as of 3/18/2011)	N	3,309
TOTAL MANHOURS (as of 3/18/2011)	N	502,817
TOTAL DMM ELEMENT INSTALLED	N	18,028
TOTAL VOLUME TREATED	CY	1,681,579
TOTAL CEMENT USED	SHTON	457,693
TOTAL TRUCK-LOADS (approx.)	N	17,500
TOTAL WATER USED	GAL	136,832,094
TOTAL CORING	N	506
TOTAL UCS TESTS	N	5,082
OVERALL AVERAGE UCS (required = 100 psi)	PSI	292
TOTAL FAILING UCS TESTS (<100 psi)	N	66
TOTAL FAILING UCS TESTS (10% allowed)	%	1.30%

May 2022

37



May 2022

38

Technology

Over 60% of the ground improvement was accomplished with the Trevi Turbo Mix (TTM) technology, single and double axis.

The TTM method was 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.



May 2022

39

Construction - continued

SR-70



May 2022

40

Construction - continued

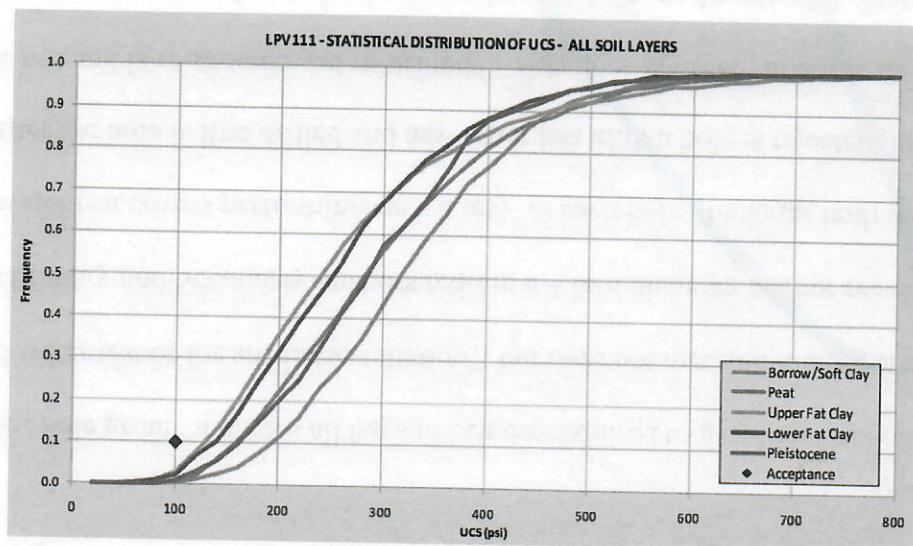
FUDO



May 2022

41

QC – Analyses



May 2022

42

Observations

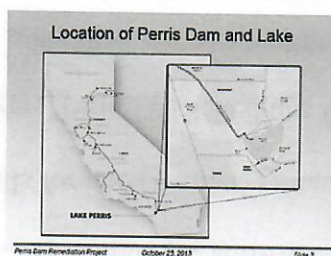
- The Phase 1 USACE Test Program was, in retrospect, an extraordinarily timely and valuable undertaking on different levels, given what was to follow in August 2005.
- The Phase 2 projects completely validated the technical and economic viability of DMM in Louisiana on a number of medium-scale jobs.
- Confidence and experience gained in Phase 2 directly influenced the decision to use DMM in LPV 111 – the largest DMM project undertaken in North America. This project has set new standards in technology, quality and procurement practices.
- Throughout the New Orleans Experience, there has been unprecedented cooperation between the Government, the consultants, the contractors, and the suppliers.



May 2022

43

2.3. Seismic Remediation of Perris Dam CDSM cells at embankment toe for liquefaction mitigation

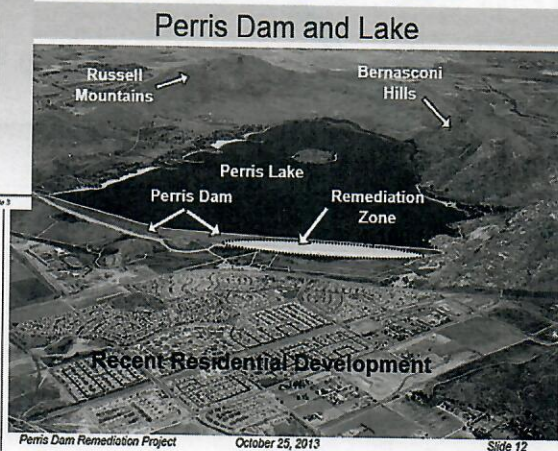


Site is located 5 miles from San Jacinto fault zone, Magnitude Mw 7.5

Dam height: 126 ft
Construction: 1970 to 1972

Base: 2013 DFI Presentation
by Mr. Mike Driller of
Dept. of Water Resources, CA

Length of remediation zone = 4,100 ft.

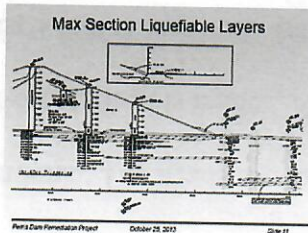


May 2022

44

Seismic Remediation of Perris Dam

CDSM cells for embankment stabilization

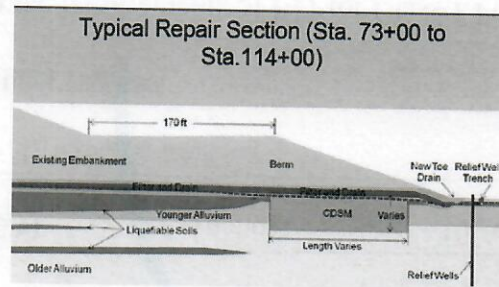


- DWR foundation study in 2005 indicated the thin sandy layers in dam foundation are liquefiable and may lose strength during a large seismic event.
- CDSM cells are designed to maintain the seismic stability. CDSM shear walls provide the resistance to the lateral force induced by the earthquake.

Cross section of Perris Dam

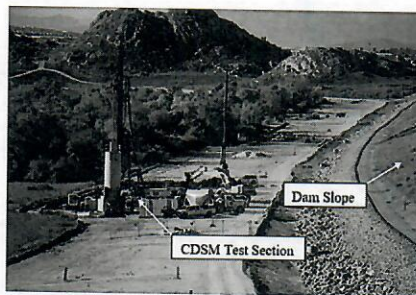
Base: 2013 DFI Presentation by Mr. Mike Driller of Dept. of Water Resources, CA & 2005 DWR Perris Dam Foundation Study Report.

May 2022



45

DWR study and test section



Sources: 1. Results of a Cement Deep Soil Mixing Test Section at Perris Dam, W.Y. Chen and M. Driller
2. DWR reports and papers

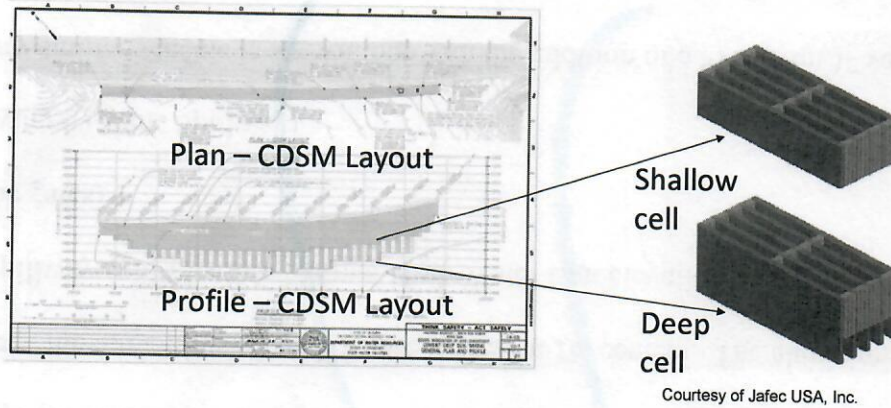
- A remedial alternative study in 2007 recommended removal and replacement of up to 25 feet of foundation soil at toe. CDSM was recommended to treat deeper portion of the foundation.
- Test sections were constructed in 2010 to evaluate CDSM and dewater & excavation construction method. It was found that water levels rebounded quickly after dewatering pumps were shut off.
- Based on the findings from test sections, DWR concluded that major excavation near the dam toe would be unsafe and both shallow and deep foundation soils need to be treated with CDSM.

May 2022

46

Plan & Profile - CDSM

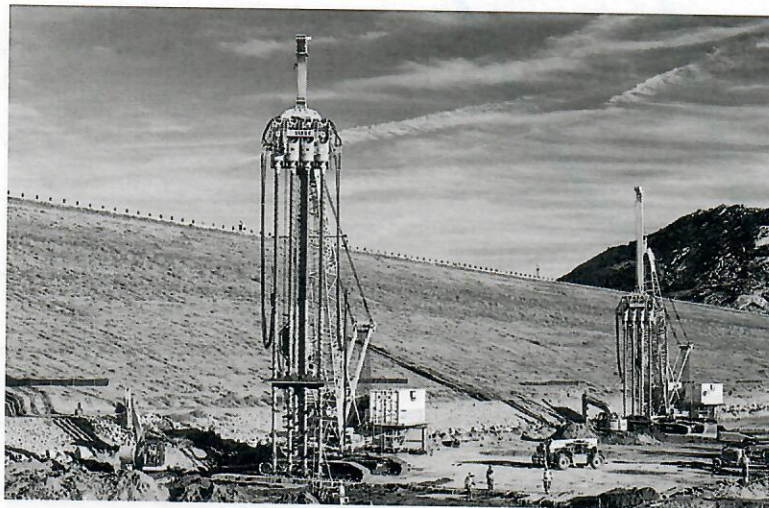
- Shallow cells & longitudinal walls: 35 feet to intercept shallow liquefiable layers
- Transverse walls – 40 to 65 feet to intercept isolated deep liquefiable pockets



May 2022

47

Full production of CDSM cells



Courtesy of JAFEC USA, Inc.

May 2022

48

Perris Lake Dam Foundation treatment



Top of CDSM cells exposed for placement
of filter and drain

Photo from site camera

May 2022

49

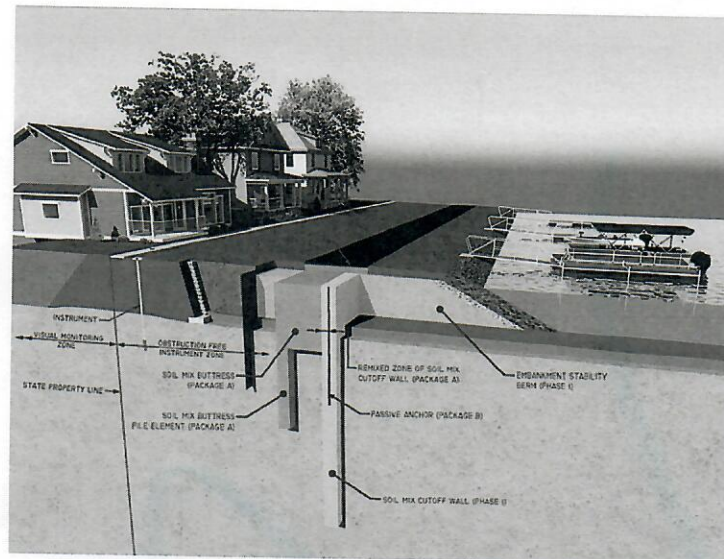
Buckeye Lake Dam, OH



May 2022

Courtesy of Gannett Fleming, Inc.

50



Rendering Courtesy of Gannett Fleming, Inc.

May 2022

51

Portage Lakes Dam, OH



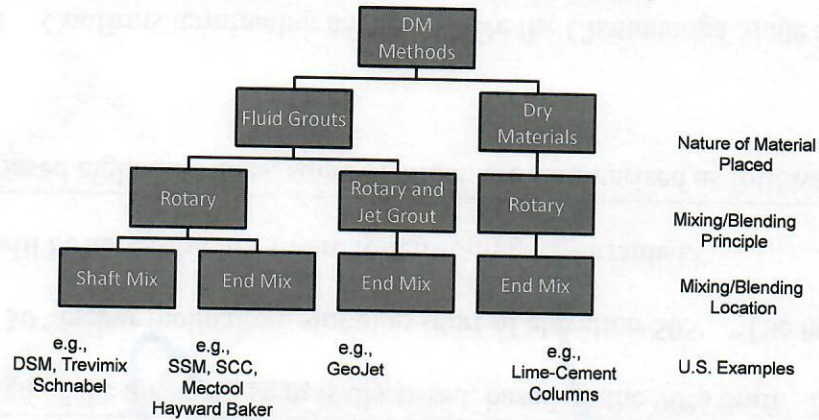
Courtesy of Tetra Tech, Inc.

May 2022

52

3. NEW ARRIVALS

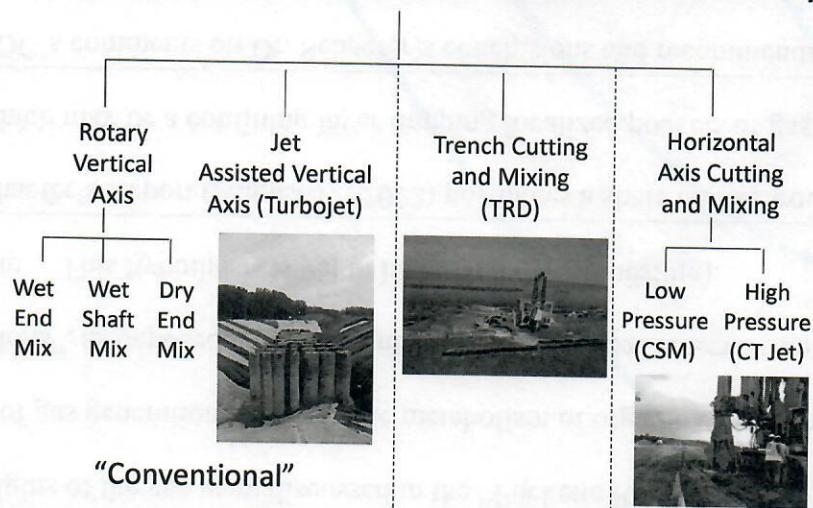
Original Classification of Deep Mixing Methods (FHWA 2000)



May 2022

53

Updated DMM Classification (Bruce, 2010)



May 2022

54

“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.



May 2022

55

“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.

May 2022

56

Herbert Hoover Dike, FL

USACE managed 4 different risk elements as follows:

1. Technology Risk: Prequalification of 3 different methods (out of 8 proposed), each with very detailed statements of prior experience.
2. Schedule Risk: Breaking down whole project into numerous smaller sections, permitting simultaneous work in several sections.
3. Project-Specific Risk: Each section predicated by a 500-foot-long Demonstration Section. Production only permitted after USACE acceptance of Demonstration Section Report. USACE also employed an external consulting group as continuity/oversight over all individual contracts. For in-situ homogeneity, extensive reliance placed on Optical Televiewer (Robertson Geologger).

May 2022

57

4. Performance Risk:

Use of Performance Specification, but very clear QA/QC and Verification criteria defining:



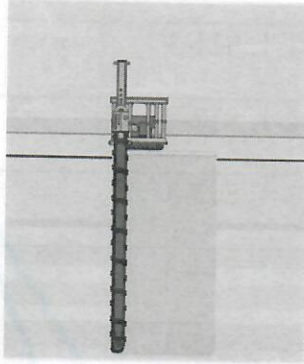
- Continuity, homogeneity, verticality;
 - 18- to 36-inch width;
 - In-situ permeability $\leq 1 \times 10^{-6}$ cm/s (in coreholes at 200-foot centers);
 - UCS 100 to 500 psi from cores, at 28 days;
 - Chemical compatibility with groundwater and soil.
- Phase 1 featured over 21 miles of cut off with 3 different construction methods. Phase 2 (over 30 miles) now underway.

May 2022

58

Continuous Trench Cutting

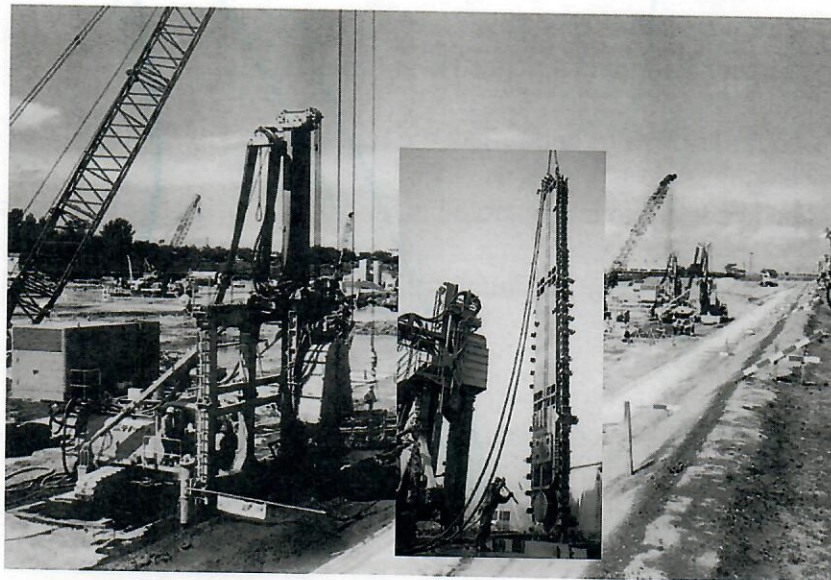
TRD (Trench Re-Mixing and Cutting Deep Wall) Method



- 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.

May 2022

59



May 2022

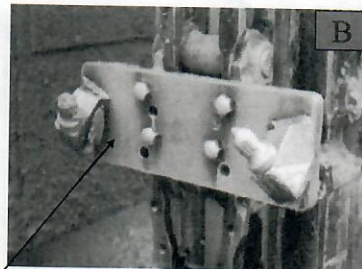
60



May 2022

61

Blades vary according to soil condition



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

May 2022

62



May 2022

63

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).



May 2022

- 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.

64

TRD

Potential Drawbacks

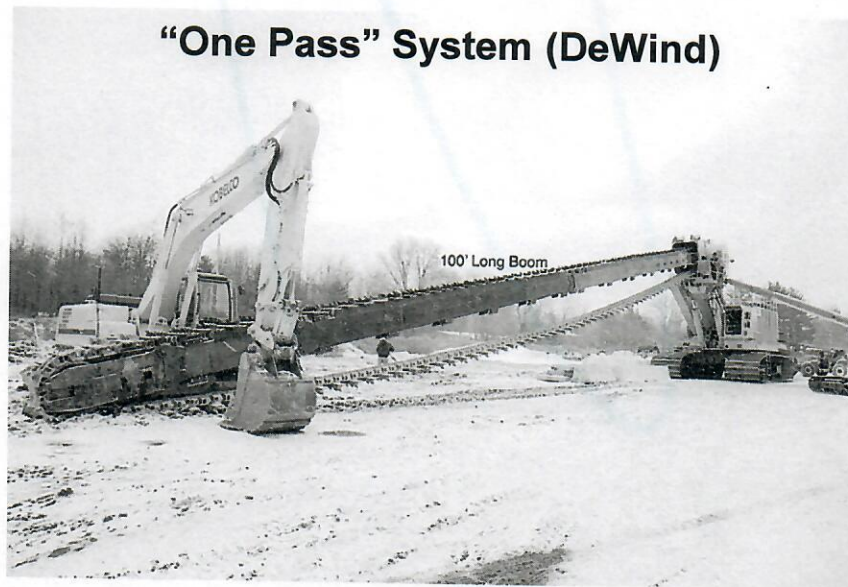
- ❖ Sharp alignment changes.
- ❖ Especially hard/massive/abrasive rock.
- ❖ Trapping of "post" in soilcrete or "refusal" on boulders/rock.
- ❖ Only one (excellent) contractor!



May 2022

65

"One Pass" System (DeWind)



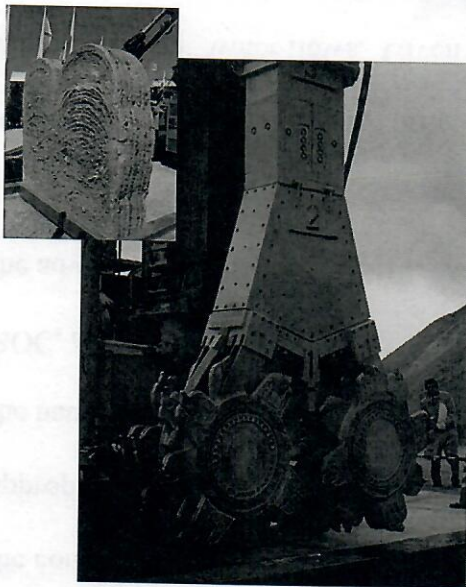
May 2022

66



May 2022

67

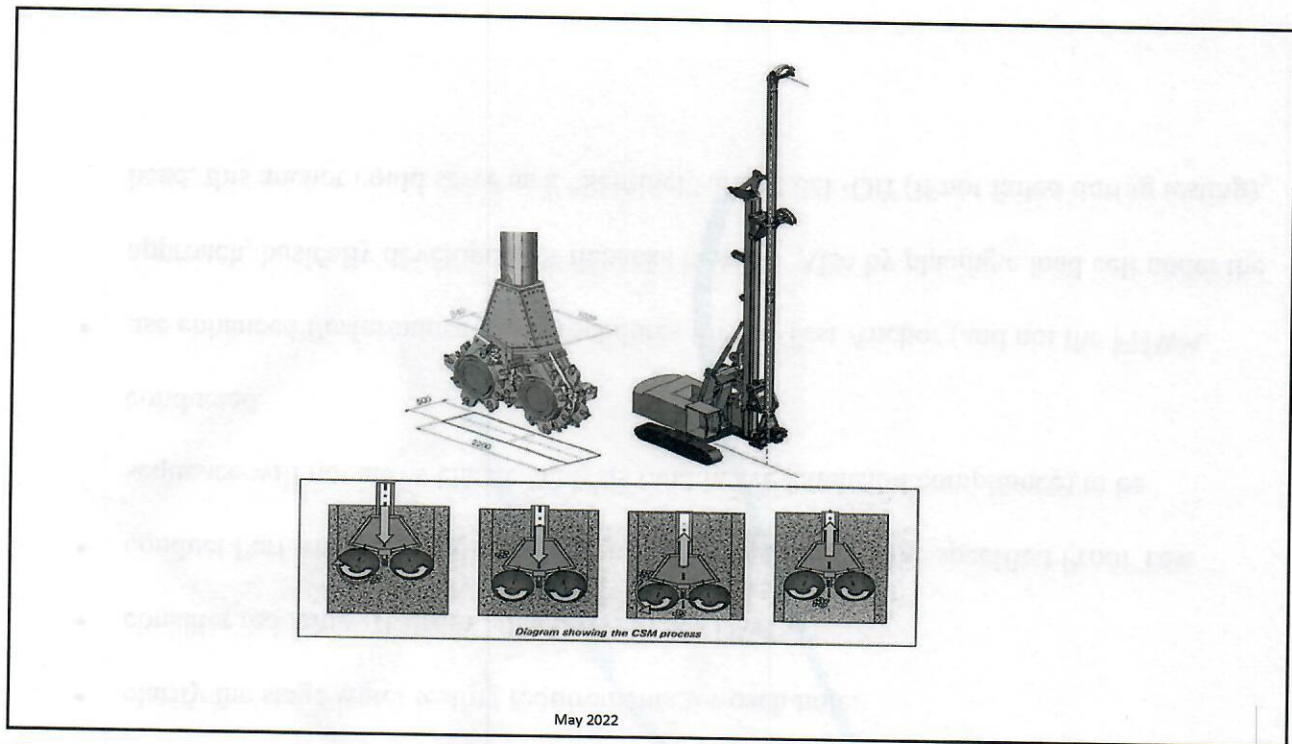


May 2022

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 40 units in service).
- Similar system developed by Trevi (CT Jet).
- Maximum depth 180 feet, 20-47 inches wide.

68



69

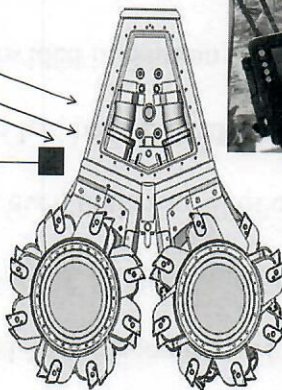
CSM Quality Control Systems

The CM 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

May 2022

70



May 2022

71



May 2022

72

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.



May 2022

73

CSM

Potential Drawbacks

- As for all DMM variants, rock, boulders and organics are challenges.
- Needs considerable headroom.
- Cost base (as for all DMM variants).



May 2022

74

At Herbert Hoover Dike, over 21 miles of cutoff were installed with 3 methods in Please 1:

- CSM (Bauer)
- TRD (Hayward Baker)
- SHS (Trevi ICOS)

A second phase of similar work has recently started totaling over 30 miles.



May 2022

75

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	5x10 ⁶ to 1x10 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)

May 2022

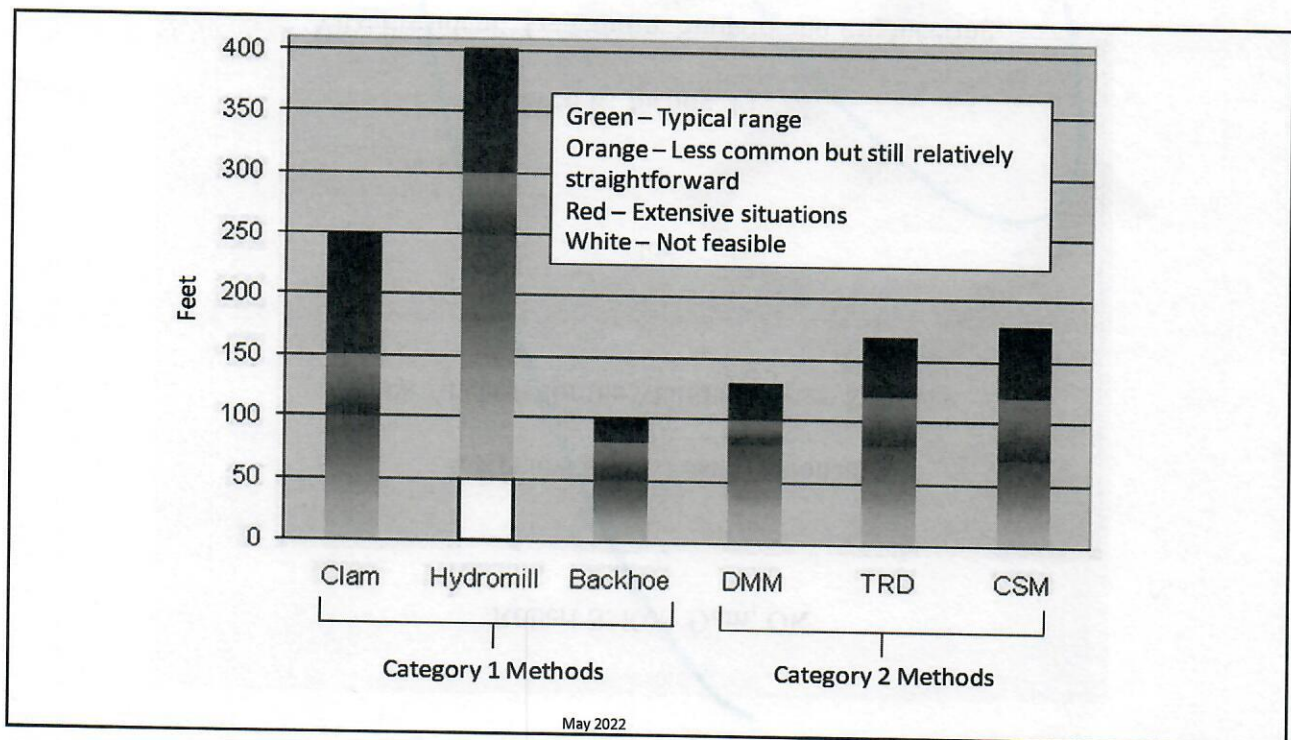
76

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 soldierpile 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 soldierpile panels	Max 180'	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

May 2022

77



78