Deep Mixing Methods Used for Levee and Dam Remediation: An Updated Classification for U.S. Practice

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ABSTRACT

In 2000, the author devised a generic classification of the various Deep Mixing Methods (DMM) techniques (FHWA, 2000). This encompassed 24 different construction systems which had been devised around the world, but principally in Japan, Scandinavia and the U.S. Since then there have been fundamental changes to the concepts of DMM: no longer do we only employ variants of the "conventional" DMM concept where mixing in the ground is carried out via the use of rotating mixing tools mounted on long vertical shafts. In addition, we now have growing experience with techniques like Cutter Soil Mix or CT Jet which blend the use of hydromill technology (i.e., the use of large cutting wheels mounted on horizontal shafts) with DMM principles, and also the TRD Method, which is basically a rather large vertical chainsaw which cuts and mixes as it advances longitudinally.

This paper updates and expands the previous classification, focusing on those techniques employed within the U.S. It also provides guidance as to the applicability, pros and cons of the respective methods.

1. Introduction

During the late 1990's, the Deep Mixing industry in the U.S. was growing rapidly, in terms of annual volume, principally as a result of major projects in Boston, MA, associated with the "Big Dig." However, the zealous attempts of the various competitor contractors to promote their "special" (often "unique") construction methodology, unfortunately led to confusion amongst potential clients of the technology. How, for example, was Deep Soil Mixing (DSM) different from Soil Mixed Wall (SMW), and while Shallow Soil Mixing (SSM) could intuitively be defined, how did any of these methods relate to the Deep Mixing Method (DMM) which was the overarching terminology used in Japan, and in the Nordic countries?

The seminal May 1996 Deep Mixing (and Grouting) Conference in Tokyo, Japan, provided the inspiration for the Federal Highways Administration (FHWA) to commission a state-of-practice survey by the current author, which led to the publication of a three-volume study in 2000 and 2001. One of the particular goals of the study was to develop a generic classification of all the DMM techniques then used or under development throughout the world, but especially in Japan, the Nordic countries, and North America. This generic classification remained valid until about 2006 when a new concept in DMM was introduced into the U.S. from Japan (where it had been developed in 1993) and from Germany/France (where a new technology had been first developed in 2003). "Conventional," or traditional DMM remains a

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popular technology in projects throughout the U.S., in its many variants, while the current huge cutoff wall projects for the protection of Herbert Hoover Dike, FL have showcased the technical and commercial benefits of the "new" technologies. It is therefore timely that a new, modified classification of the DMM techniques is presented to ensure clarity and assure understanding for all industry segments.

2. The Original Classification

The FHWA (2000) classification was based on an analysis of 24 different methods which had been described in the DMM literature to that point. It was based on the following operational characteristics:

- The method of introducing the "binder" into the soil: wet (i.e., pumped in slurry or grout form, or blown in pneumatically in dry form). Classification is therefore W or D.
- The method used to penetrate the soil and/or mix the agent: purely by rotary methods (R) with the binder at relatively low pressure, or by a rotary method aided by jets of fluid grout at high pressure (J). (Note: Conventional jet grouting, which does not rely on any rotational mechanical mixing to create the treated mass, was out of the scope of the study.)
- The location, or vertical distance over which mixing occurs in the soil - in some systems, the mixing is conducted only at the distal end of the shaft (or within one column diameter from that end), while in the other systems mixing occurs along all, or a significant portion, of the drill shaft. Classification is therefore E or S.

The classification is shown in Figure 1. To illustrate its workings, Geo-Con's DSM method uses grout and rotary mixing energy alone over a large proportion of the shaft, and thus qualifies as WRS. Conversely, the DJM method (Dry Jet Mixing), as used by many Japanese contractors, uses dry binder and rotary mixing energy alone supplied via a tool at the bottom of the shaft, and thus is classified as DRE.

With three bases for differentiation, each with two options, there are theoretically eight different classification groups. However, in practice, there are only four groups since wet grout, jetted shaft mixing (WJS) and dry binder, rotary, shaft mixing (DRS) do not exist, and no jetting with dry binder (DJS or DJE) has been developed.

While many of the systems shown in Figure 1 were fully operational, some remained in the experimental or developmental stages. For example, the FGC-CDM system used modified CDM equipment to inject flyash (F), gypsum (G), and cement (C) to create economical low-strength treated soil volumes. This concept was commissioned to investigate potential uses for the huge volumes of flyash produced annually by Japanese coal burning power plants. Research continued in Finland into the use of waste products from their steel manufacturing industry (slag) as a potential binder. The Rectangular 2 and the JACSMAN (Jet and Churning System MANagement) methods appeared to be at the full-scale field-test stage, while Rectangular 1, Soil Removal Technique, LDis, and Spread Wing had been reported to have

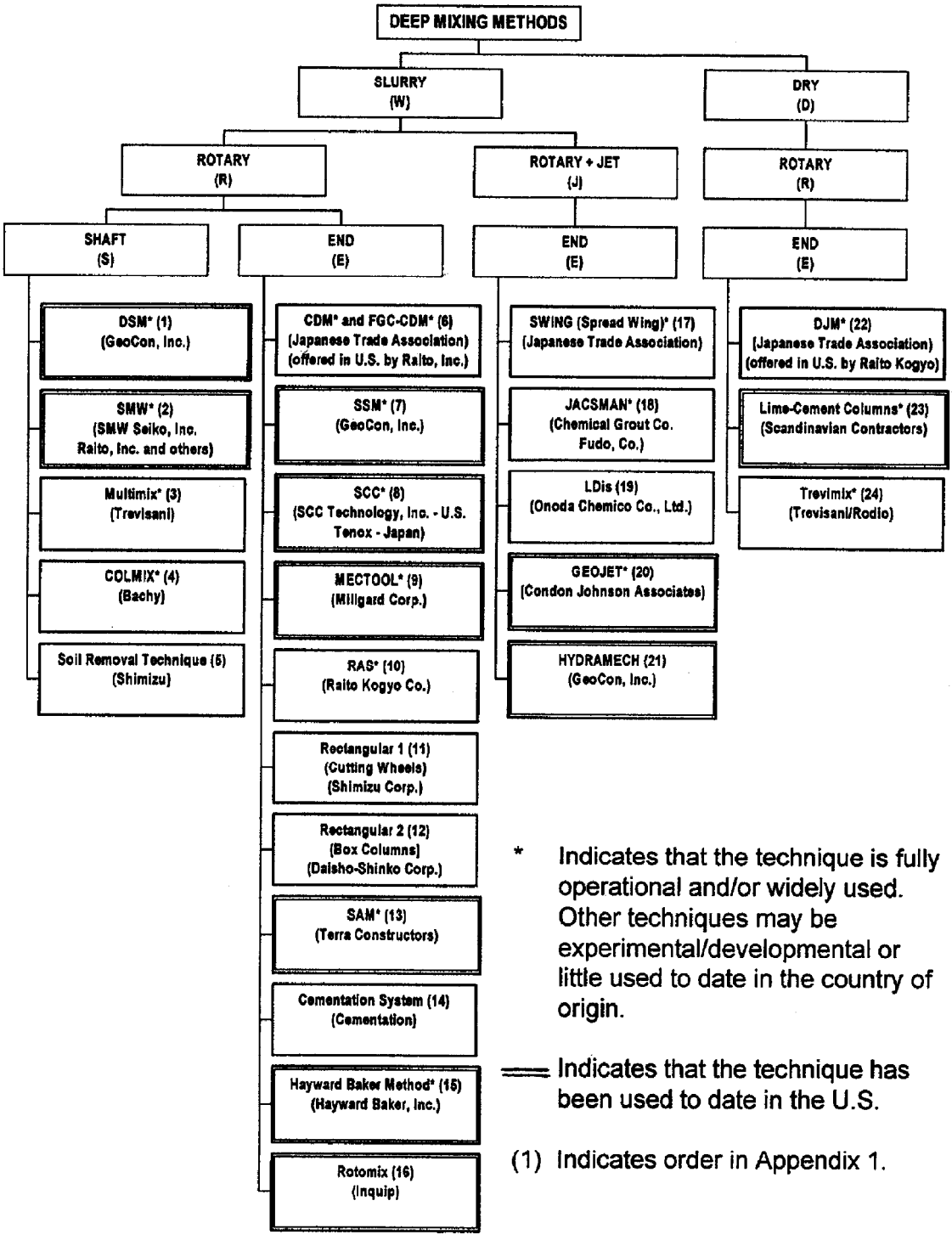

Figure 1. Classification of Deep Mixing Methods based on "binder" (Wet/Dry); penetration/mixing principle (Rotary/Jet); and location of mixing action (Shaft/End).

actually been used in a full-scale project. LDis (Low Displacement Jet Column Method), like many of the later developments, was a modified jet-grouting derivative in which mechanical means were used to reduce horizontal and vertical movements during soil treatment.

What is clear, of course, is that all of these variants featured vertical axis machines, mixing the ground by rotation and/or jetting around these axes. These "conventional" methods have proved most attractive and effective in projects where:

- The ground is neither very stiff nor very dense, nor contains boulders or other obstructions.
- Where treatment depths of less than about 120 feet are required.
- Where there is relatively unrestricted overhead clearance.
- Where a constant and good supply of binder can be ensured.
- Where a significant amount of spoil can be tolerated.
- Where a relatively vibration-free technology is required.
- Where treated or improved ground volumes are large.
- Where "performance specifications" are applicable.
- Where treated ground strengths have to be closely engineered (typically 15-700 psi).

In overview, the particular advantages of "conventional" DMM techniques include:

- There are low vibration levels and moderate noise generation.
- Applicability in a wide range of soils.
- Provision of good levels of homogeneity and continuity in appropriate conditions.
- Relatively high productivities can be provided.
- The scale of the project is large.

In contrast, conventional DMM is much less attractive in conditions where:

- Large, heavy and tall equipment is problematical due to space restrictions on site.
- Treatment depth exceeds 120 feet (vertical).
- There are very dense or stiff soils, and/or where organics and/or boulders are present.
- Project scope is limited (mob/demob costs are relatively high).

3. The Two New DMM Concepts

These were described at length by Bruce (2009). The older, the TRD Method (Trench Remixing and Cutting Deep Wall) was developed in Japan in 1993, introduced in the U.S. in 2005, and has a 170-foot maximum depth capability. It builds 18- to 34-inch-wide soilcrete cutoffs by employing basically a large vertical chainsaw, which cuts and mixes the cutoff simultaneously in a longitudinally progressive fashion.

Its particular advantages include:

- Provides continuous, homogeneous, joint-free wall through all soil and many rock conditions.
- Productivities can be very high in appropriate conditions: Gularte et al. (2007) report instantaneous productivities (i.e., production when the machine is actually in operation) of 400 square feet of wall per hour in the sands at Alimitos, CA and significantly higher productivities have been achieved at Herbert Hoover Dike, Florida. The potential of the machine is best suited to "long runs." Excellent historical data from a wide range of ground conditions are available upon which to base production estimates.
- A very high degree of QA/QC can be applied to assure in real time verticality (or the required inclination), continuity and in situ wall properties. Post-construction verification of as-built properties (strength, permeability, homogeneity, elastic modulus) can readily be conducted with conventional, quality coring and/or wet grab sampling.
- The cutting teeth on the chain can be adjusted to best suit ground conditions.
- TRD can operate in headrooms as low as 20 feet (although 25 feet is a more comfortable minimum) regardless of wall depth.
- The machine and its associated grout mixing plant are relatively modest in size, and extremely quiet and "tidy" in operation.

Particular potential drawbacks include:

- Sharp changes in alignment cannot be made without extracting, reorienting and replacing the cutting post.
- Particularly abrasive and/or hard and/or massive rock will markedly reduce productivities and increase wear on the chain, the driving wheel and the bottom idler.
- The cutting post may become trapped in soilcrete which has hardened unexpectedly rapidly, or may "refuse" on particularly severe "nests" of boulders or hard rock horizons.

The newer method, the CSM (Cutter Soil Mix), was a joint development between Bauer Maschinen and Bachy Soletanche in Europe, and was first used in North America (Vancouver BC) in 2006. It is an adaptation of cutter (hydromill) technology long used for the excavation of diaphragm walls under bentonite slurry: cutting wheels are mounted on horizontal axes supported on a rigid steel frame. CSM, however, features the injection of grout during insertion and withdrawal to create soilcrete panels to depths of 180 feet and widths of 25 to 60 inches. As for TRD, the real time controls over installation parameters are exceptional, assuming the construction of high quality, homogeneous, continuous, vertical cutoffs.

Particular advantages of CSM include:

- Continuity of the wall is provided by very strict control of panel verticality in real time.
- The soilcrete is relatively homogeneous and the grout properties can be designed to provide specific parameters.

- Applicable in all soil conditions, including dense/stiff deposits.
- Cutting teeth can be quickly adjusted to different soil conditions.
- CSM equipment can be mounted on a wide range of “conventional” carriers.
- Productivity can be very high in appropriate conditions.
- The method can easily accommodate sharp changes in wall alignment.
- Relatively quiet and vibration free.

Particular potential drawbacks include:

- As for all DMM variants, boulders and other obstructions, and very dense deposits, or rock-like layers will severely impact feasibility and productivity. Also, homogeneity will be challenged by very plastic and/or organic sediments, which, of course, can be removed in advance, as is the case at Herbert Hoover Dike, FL.
- The typical machine requires considerable headroom and access.

Table 1 provides a summary of the properties of each of the three fundamental DMM types.

4. The New Classification

In considering how to accommodate TRD and CSM into the preexisting classification of Figure 1, it is clear that these two methods are so fundamentally different in operating principle that they merit independent status, under the overall DMM umbrella. The “traditional” DMM with its vertical axis mixing and more than 20 variants retains its original structure. TRD, in very large part the original Japanese development, but most recently being challenged by smaller but decidedly similar European techniques, is an extraordinary and unique concept. Similarly, CSM, as practiced now independently and under different names by its European parents, and including the CT-Jet method of Trevi, has also created a distinctive nucleus of techniques.

The new classification is shown in Figure 2 and it is hoped that this will bring clarity and understanding to the world of Deep Mixing — and especially for the owners considering its use.

Table 1. Summary of Category 2 techniques characteristics.

Method	Principle	Wall Dimensions		Typical Properties of Soilcrete		Costs		Relative Benefits/Problems	
		Depth	Width	UCS	K	Mob/Demob	Unit Prod.	Pros	Cons
Category 2 – Mix in Place									
Conventional DMM	Vertically mounted shafts are rotated into the soil creating panels of soilcrete	Maximum practical about 120'	20-40"	100-1,500 psi	$5x10^{-6}$ to $1x10^{-8}$ cm/s	Moderate-High	Low in sympathetic soil conditions to Moderate/ High in difficult conditions	• Low vibrations and noise • Experience • Several practitioners in U.S. • High productivity • Good homogeneity	• Large equipment needs good access and substantial headroom • Depth limitation • Very sensitive to obstructions • Variable homogeneity with depth due to limited vertical mixing
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-High	Low- Moderate	• Continuity of cutoff is automatically assured (no joints) • Homogeneity (especially vertically) • Productivity • Quality • Quick adaptability to wide range of ground conditions • Low noise and vibrations • Low headroom potential (20') • Inclined diaphragms possible • Wide range in cutoff properties can be closely engineered • Very high degree of real time QC • Relatively compact equipment	• Difficult wall geometries (sharp turns) • Medium-hard rock, and boulder nests (will reduce productivity and increase wear on key components • Currently only one U.S. contractor • Requires very specialized equipment • Cutting post may become trapped in the wall or may "refuse" on nests of boulders or hard rock

(continues)

Method	Principle	Wall Dimensions		Properties of Backfill		Costs		Relative Benefits/Problems	
		Depth	Width	UCS	K	Mob/Demob	Unit Prod.	Pros	Cons
CSM	Cutting and mixing wheels mounted on horizontal axes create vertical soilcrete panels	Typically 140′ with Kelly but Maximum 200′ with cable suspension	22-47" with trials to 60"	70-3,000 psi	10^{-6} to 10^{-8} cm/s	Low-Moderate	Moderate	• Panel continuity/ verticality closely controlled • Homogeneity • Productivity • Adaptable to conventional base carriers • Wide range in cutoff properties can be engineered • Can accommodate sharp geometry changes • Applicable in nearly all soil conditions • Cutting teeth can be quickly adapted • Relatively quiet and vibration-free • Fewer joints than conventional DMM • Can change parameters for different soil types • Low headroom potential (15′ min)	• Rock, boulders and other obstructions • Requires considerable headroom

Key to Costs (2010 Figures)

Mob/Demob		Unit Costs (i.e., cost per square foot of cutoff)	
< $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

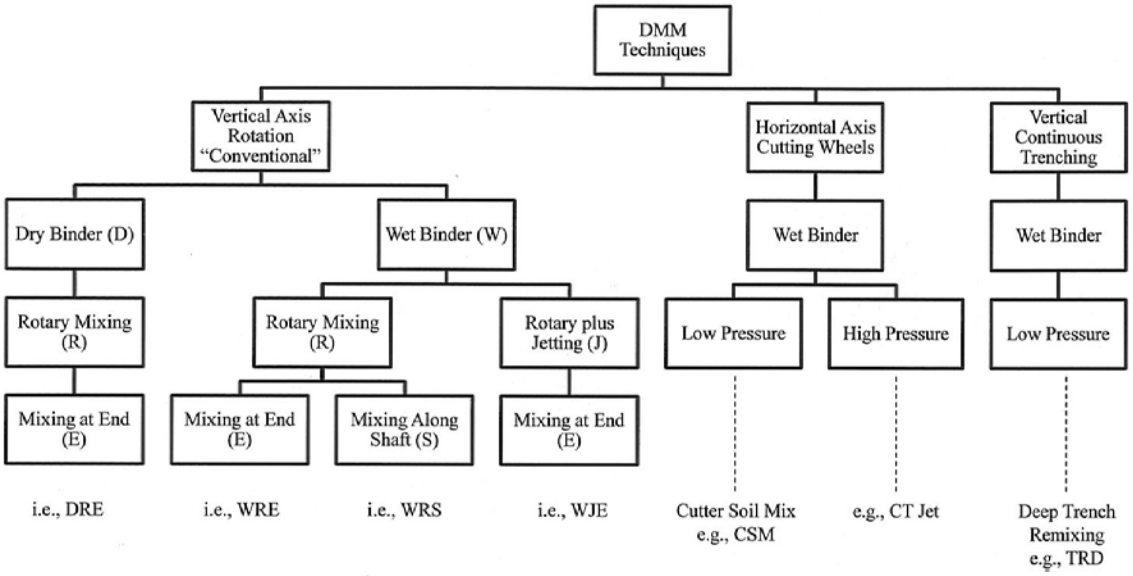

Figure 2. New DMM classification.

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