DEEP MIXING IN THE UNITED STATES: MILESTONES IN EVOLUTION

Dr. Donald A. Bruce, Geosystems, L.P., Venetia, PA 15367, USA, Phone: 724-942-0570, Email: dabruce@geosystemsbruce.com

Abstract The Deep Mixing Methods (DMM), in their current forms, have been employed in the United States since 1986, although an earlier version had seen service from 1954. The earlier developments were strongly influenced by practices in the Nordic countries and Japan, while by the late 1980's several DMM systems had been developed in the U.S. itself. Since then, DMM has continued its evolution, principally via the challenges of a series of large, landmark projects, but also via distinct, significant technological advances. This paper highlights the key points in the history of DMM in the U.S., and provides an overview of the different methods currently in use.

In the Beginning

It is a common misconception that the history of applications of the Deep Mixing Methods (DMM) in the United States dates from 1986 when SMW Seiko Inc. — a subsidiary of Japan's Seiko Kogyo Company — was established in the Bay Area. However, the author believes that Intrusion Prepakt Co.'s patented MIP (Mixed in Place) system had been used, albeit sporadically (about 30 projects are recorded), since 1954 (FHWA 2000, 2001). Ironically, by 1961 this single auger method had been extensively used under license in Japan for excavation support and groundwater control — by the Seiko Kogyo Company. By 1972, the original MIP technique had been succeeded by more advanced Japanese methods, involving multiple augers. Intrusion Prepakt have long since become defunct.

The first systematic studies of contemporary Deep Mixing Methods in Japan began in 1967 when the Port and Harbor Research Institute of the Ministry of Transportation began laboratory testing using granular and powdered lime for treating soft marine soils. Fundamental studies continued through the early 1970's, by which time the development of industrial scale equipment was well advanced, having its first application on a marine trial near Haneda Airport. Coincidentally, laboratory and field research also began in 1967 in Sweden ("Swedish Lime Column Method") for treating soft clays using unslaked lime. Reportedly the progenitor was a Norwegian, Kjeld Paus, who had made observations on fluid lime columns in the U.S. It would seem that developments in Japan and the Nordic countries proceeded independently until 1975 when the technology leaders from each group (Broms and Boman; and Okumura and Terashi, respectively) presented their — very similar — findings at a conference in Bangalore, India. Limited technical exchanges ensued thereafter.

Whereas the Nordic developments continued to focus on the use of dry reagents (cement and lime) and relatively light equipment compatible with operating on and in very soft clays and organics, the Japanese progressed into the use of fluid reagents (cement-based grouts) and heavier equipment for both marine and land-based projects. Thus, by 1986, there were a large number of proprietary (wet and dry) DMM systems in Japan, and a rapidly growing market already by then accounting for over 12,000,000 m^3 of ground treatment.

In retrospect, therefore, it is rather surprising that SMW Seiko's move to the U.S. was not replicated by other Japanese contractors (e.g., Tenox and Raito) until several years later, while Lime Cement Columns were not installed commercially in the U.S. until 1996 (by Stabilator). Instead, the trend in the U.S. market was for American contractors to develop their own multi-axis systems, with Geo-Con leading in 1988 with DSM (Deep Soil Mixing) and, in 1989, with single-axis SSM (Shallow Soil Mixing), primarily for environmental remediations. Key dates are summarized in Table 1.

Table 1. Key dates in DMM evolution in the U.S.

1954	Original MIP System (Intrusion Prepakt)
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
2001-2003	Desk, Bench and Field Tests, New Orleans
2001-2005	National Deep Mixing Research Program (States Funded)
2003	International Conference in New Orleans
2005	Hurricanes Katrina and Rita
2006	Task Force Guardian, New Orleans
2006	CSM brought to Canada and TRD brought to U.S.
2006-2007	Deep Mixing at Tuttle Creek Dam, KS
2007-2013	National Deep Mixing Project Revised
2008-2012	Cutoff Walls at Lake Okeechobee
2010-2011	LPV 111, New Orleans, LA
2012	International Conference in New Orleans
2013-Present	Increasing DFI support for DMM, especially for dam and levee remediation

Some Landmark Projects

DMM suddenly came to the fore in the U.S. in 1987 when the Geo-Con led alliance with SMW Seiko commenced the seismic retrofit of the foundation of Jackson Lake, WY. The DMM alternate was used principally to create an interlocking "honeycomb" of soilcrete columns, as well as a seepage cutoff. This project involved over 120,000 linear meters of columns and was widely and justifiably publicised in the technical press, particularly with regard to the information it generated on soilcrete properties.

Following a period when DMM was principally used for environmental applications and increasingly for small earth retention projects (when suitably reinforced and anchored or braced) the Nicholson-Seiko JV used the technique from 1992 to 1994 to provide about 37,200 m^2 of earth support walls at the Ted Williams Tunnel Approach (Contract CO7A1) in Boston, MA. Much was learned about the construction challenges of DMM in glaciated terrains, and about the durability of such walls in freeze-thaw conditions. Confidence in the technique remained at a high level in the Boston Central Artery Project, culminating in the second major DMM project in the city in the late 1990's when about 420,000 m^3 of soil were treated by a major JV again including Nicholson and SMW Seiko during the construction of the Fort Point Channel contract and adjacent structures. One estimate has it that, by 1998, more than 20 excavation support walls had been built with DMM in the U.S., including three involving the "gravity wall" concept, without anchors or braces. These projects included walls for the Cypress Freeway Replacement Project, CA, the Islais Creek Sewerage Scheme, GA, the Marin Tower, HI, the Lake Parkway, WI, and the LA Metro, CA.

Suitably inspired, by the late 1990's the number of competitors had grown, with systems being offered by well-established U.S. contractors such as Hayward Baker, Schnabel, Malcolm and Condon Johnson; Japanese contractors such as Raito, Fudo, Tenox and Jafec; and European-owned U.S. subsidiaries such as TreviICOS, Underpinning and Foundations, Soletanche, and Bauer; as well as a number of primarily environmental remediation contractors, frequently the off-shoot of the original Geo-Con company.

Other notable transportation-related projects of the period included Stabilator's dry DMM projects at I-15 UT, (1997) and in San Francisco, CA (1998), Raito's wet DMM project at Woodrow Wilson Bridge, VA (2000), and Hayward Baker's 275,000 m^3 of dry, shallow, bulk mixing at Jewfish Creek, FL in 2005-2006.

Geo-Con had built a DMM cutoff wall through Lockington Dam, OH and similar dam/levee cutoffs were installed in the early 1990's by Seiko and Raito, at a number of projects including Cushman Dam, WA, Lewiston, ID, and Sacramento, CA. However, the main application for DMM on hydraulic structures has been for seismic retrofit, and from the early 2000's onwards, major DMM installations had been recorded at Sunset North Basin Dam, CA; Clemson Upper and Lower Diversion Dams, SC; and San Pablo Dam, CA, all by Raito. A landmark, full-scale test of various DMM (and other) techniques was conducted in 2006 by TreviICOS at Tuttle Creek Dam, KS, although the subsequent production works employed a slurry wall method (Mauro and Santillan, 2008).

The New Orleans District of the U.S. Army Corps of Engineers (USACE) had, in 2001, the foresight to organize and fund a full-scale demonstration of (dry) DMM in their soft cohesive, organic soils (Cali et al., 2005). This field test, which involved input from specialists in the U.S., Japan and Sweden, was a fascinating technical success: DMM could be made to work in the putty-like soils of the Mississippi delta (Photographs 1 and 2). However, DMM as a routine technique for solving foundation problems in the region was judged to be either — or both — too "radical" or too costly (depending on the particular viewpoint), and so the idea was, politely, shelved. Then, in August of 2005, the historic Crescent City was impacted by Hurricanes Katrina and Rita, and traditional paradigms were overturned in the face of necessity and expediency.

Photograph 1. Excavated dry DMM test column, New Orleans, LA (Cali et al., 2005)

Photograph 2. One of three test cells, each with a different replacement ratio, fully loaded with 1 million kilograms of steel (177 kN/m^2) (Cali et al., 2005).

Task Force Guardian was formed by the USACE and, by early 2006, DMM work, both wet and dry, was being conducted on an emergency basis on four projects involving gate construction and levee remediation (Photograph 3). In the following 4 years, a further 6 projects were conducted under somewhat more relaxed conditions by the same two contractors — Hayward Baker (Dry) and Raito (Wet) (Table 2). These relatively modestly-sized projects were the forerunners for the massive LPV 111 project, a 8.8 km long component of the Lake Pontchartrain and Vicinity Hurricane Protection Scheme. This project involved over 1.3 million m^3 of wet DMM, to improve the soft foundation soils, prior to the placement of over 0.8 million m^3 of dry levee fill (Bruce et al., 2012). The DMM was conducted principally by TreviICOS (with contributions from Fudo Construction) using their proprietary "Turbo Mix" system (Photograph 4). Over 17,000 soilcrete elements were installed employing over 380,000 tonnes of slag-cement in a period of about 13 months. Given the intense pressure on schedule, the USACE employed the ECI (Early Contractor Involvement) concept whereby the successful contractor was selected on a 10% design basis. This project remains by far the largest DMM application in the U.S., and one of the largest in the world. It set new standards in productivity and quality in North American Deep Mixing practice (Schmutzler et al., 2012).

Photograph 3. Wet DMM operations from barge at Orleans Avenue Canal, New Orleans (Bruce et al., 2012).

Photograph 4. Double axis Soilmec deep mixing machine at LPV 111, Louisiana.

Table 2. Summary details of Deep Mixing Projects Conducted (all for USCE) in New Orleans, 2006-2010 (Bruce et al., 2012).

PROJECT NAME	START DATE	APPLICATION	DETAILS	CONTRACTOR
17th 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.

Project Name	**Start Date**	**Application**	**Details**	**Contractor**
IHNC Reach III (paper in this Conference)	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.

New Arrivals

All of the numerous vertical axis DMM techniques may be referred to as "conventional." As shown in Figures 1 and 2, these have now been supplemented by two other groups of techniques, broadly classified as "Horizontal Axis Cutting and Mixing," and "Vertical Continuous Trenching." The former is most commonly represented by the CSM (Cutter Soil Mix) method, developed jointly between Bauer Maschinen of Germany, and Bachy Soletanche of France in 2003, although Trevi have a not dissimilar system called CT Jet. By 2011, over 150 projects had been completed worldwide, with a significant number in North America. CSM is an evolution of earlier trench cutter (hydromill) technology, whereby grout is injected via the cutter as it is advanced and withdrawn, to create individual rectangular-shaped soilcrete panels (Photograph 5).

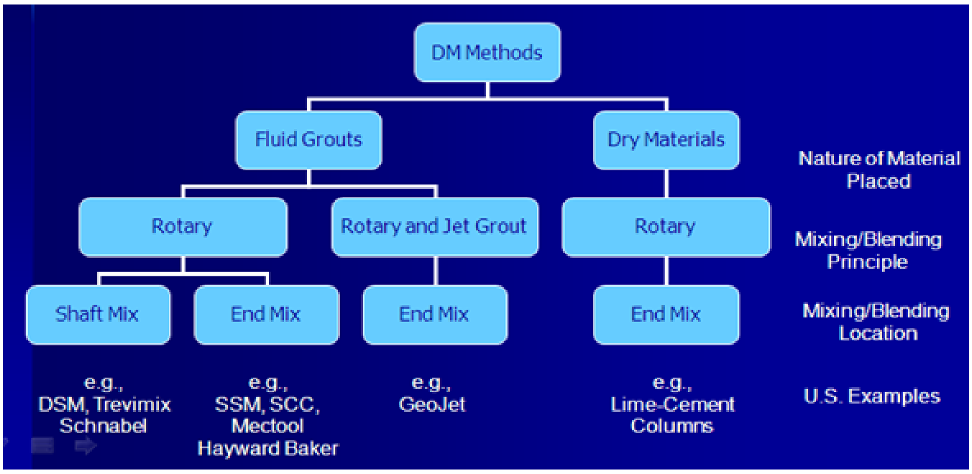


Figure 1. Original classification of Deep Mixing Methods (FHWA, 2000).

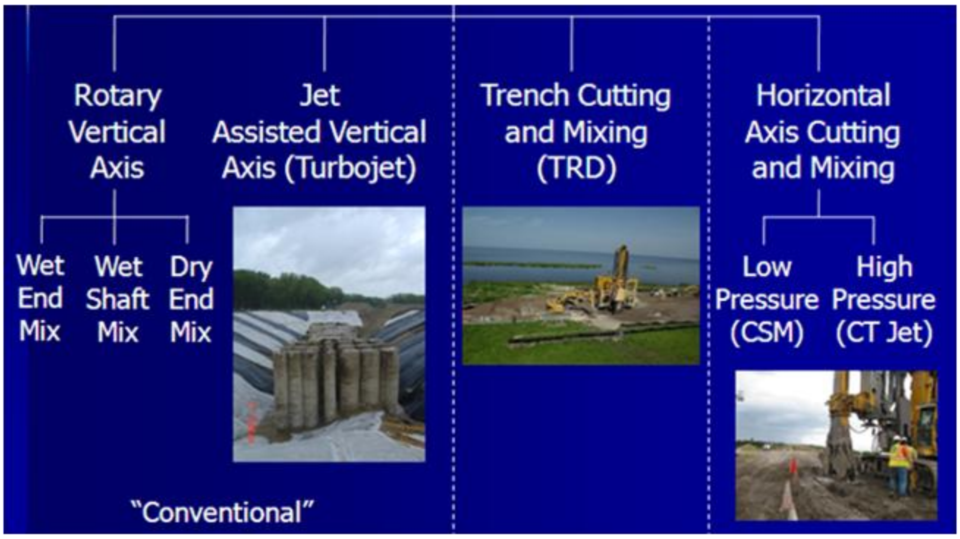
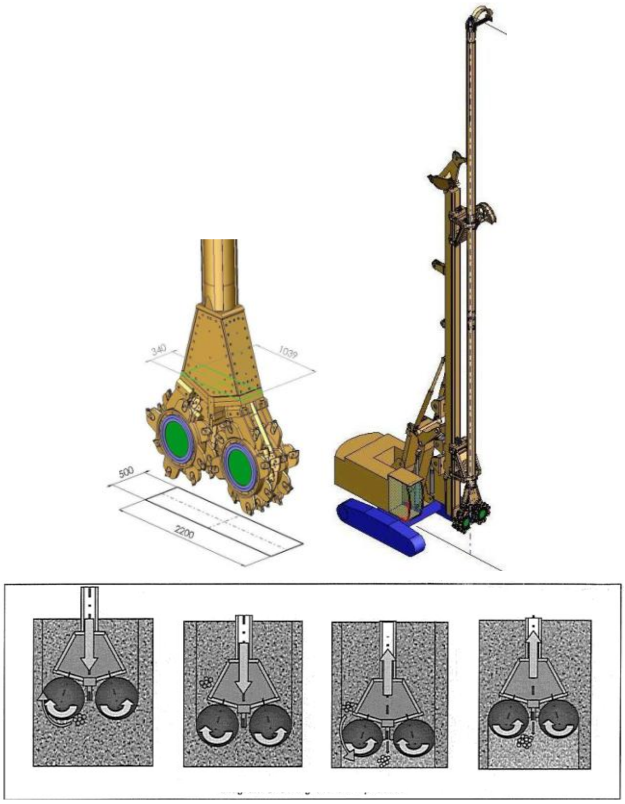


Figure 2. Updated DMM classification (Bruce, 2010).



Photograph 5. Diagram showing the CSM process.

The largest CSM project yet conducted in the U.S. is the construction by Bauer of several miles of 600-mm wide cutoff, to depths of over 20 m in Herbert Hoover Dike, FL. In Canada, the work recently completed by Golder Construction for foundation improvement at Kitimat, BC, is the most impressive of the many projects undertaken since 2006. In all the applications, the quality of the Deep Mixing, in terms of the homogeneity, strength and permeability of the soilcrete, has been exceptional.

Deep Mixing by Vertical Continuous Trenching is represented most notably by the TRD (Trench Cutting Remixing Deep Wall) Method. This is a 1993 Japanese development introduced to the U.S. by Hayward Baker in 2006. It uses a full-depth, vertical "cutter-post" with a peripheral cutting chain (Photograph 6). As this vertical tool is drawn through the ground, the crawler-mounted chainsaw cuts and mixes the soil with grout (injected from ports on the post). It provides a continuous wall, without joints, with a very high efficiency of vertical mixing. Widths of 560 to 840 mm and depths to 55 m are feasible, in appropriate conditions, i.e., those that are "rippable." TRD has been used on several U.S. projects to date, by far the largest being — as for CSM — at Herbert Hoover Dike, FL, for the construction of many kilometers of cutoff wall.

Photograph 6. TRD Method equipment.

Studies, Researches and Conferences

Deep mixing expertise has experienced substantial growth and dispersion in the U.S. over the past two decades through a combination of contractor innovations, design creativity, research endeavours, and several notable publications and conferences, as well as numerous seminars and short courses. Deep mixing contractors continually improve their tooling and their binder delivery and mixing processes to enhance mixture quality and productivity. Such innovations include adding stationary blades to single axis mixing equipment and delivering slurry under high pressure through nozzles located along the arms of mixing blades. Contractors and researchers have developed a greater understanding of the ways that different binders and mixture proportions influence compressive strength, shear strength, tensile strength, ductility, and stiffness especially in the various inorganic and organic soils, although more work remains to be done in this area. Designers and researchers in the U.S. have developed improved analytical techniques to permit efficient design against multiple failure modes and to successfully integrate design, construction, and QC/QA to reliability account for variability in property values. Important progress has been made in design to resist seismic loading and mitigate liquefaction, although again more work remains in this area.

Significant practice-oriented research in the U.S. was funded in the early 2000's by the National Deep Mixing Program, which was a collaborative effort among the FHWA and ten state DOTs, and by separate initiatives by FHWA and state DOTs. The U.S. Army Corps of Engineers sponsored the test program in New Orleans described previously, as well as development of simplified analysis and design procedures that capture important features of deep mixing foundation systems for levees and floodwalls in soft ground. The USACE design procedures formed the basis for a design manual that was prepared for FHWA for transportation applications. The U.S. National Science Foundation has funded and continues to fund some basic research that has practical applications.

U.S. practitioners and researchers have learned and shared much of this information through international and domestic conferences, including: the IS-Tokyo 1996 conference on Grouting and Deep Mixing; the third and fourth International Conferences on Grouting Deep Mixing held in 2003 and 2012 in New Orleans; the Deep Mixing 2005 conference in Stockholm; and the 2009 International Symposium on Deep Mixing in Okinawa. The proceedings from these conferences are invaluable resources. Other publications of importance include:

- The three-volume series of FHWA state of practice reports (2000, 2001)
- *The Deep Mixing Method: Principle, Design, and Construction* (2002)
- The USACE deep mixing design guide for levees and floodwalls (2011)
- *Specialty Construction Techniques for Dam and Levee Remediation* (2012)

- *The Deep Mixing Method* (2013)
- The FHWA design manual for embankment and foundation support (2013)

The Deep Foundations Institute has sponsored several well-attended seminars and short courses that have featured deep mixing, including those in New York in 2008, New Orleans in 2011 and 2012, San Francisco in 2013, and Miami in 2014.

The Way Forward

After 27 years of application in the U.S., DMM is, technologically speaking, in rude health. "Conventional" methods are continuously being modified by experienced and well-resourced Specialty Contractors to enhance quality and productivity and, in this regard, the utilization of high grout injection pressures is a good example. Similarly, the more recent CSM and TRD methods provide very competitive DMM alternatives in appropriate applications and conditions while again providing exceptional quality and homogeneity. A feature common to all DMM techniques is the use of real time electronic monitoring and control of mixing parameters — data which are stored, again in real time, and transmitted to remote management centers, via telemetry. The only cloud on the horizon would seem to be a relative dearth of "big jobs" now that the huge Federal projects such as those in Florida, Louisiana and Sacramento are winding down. However, Nature does have a peculiar way of creating "wake-up calls" resulting in waves of new opportunities for ground engineers.

Credits and Kudos

This brief review reflects the efforts, skills, experiences and commitments of many practitioners in the Deep Mixing field, many of whom have written excellent papers not specifically cited in this brief overview.

In North America, one can name, in no particular order of merit, Brian Jasperse, George Filz, Chris Ryan, George Burke, David Yang, David Weatherby, Osamu Taki, James Johnson, Heinrich Majewski, Dennis Boehm, Eddie Templeton, Pete Cali, Steve Day, Wes Schmutzler, Brian Wilson, J.R. Takeshima, Masaru Sakakibara, Dave Sandstrom, Pete Nicholson, Jonathan Fannin, Filippo Leoni, Ken Andromalos, Tom Cooling, David Druss, Dominic Parmentier, and Dave Miller.

Our main overseas influences have been Masaaki Terashi, Masaki Kitazume, Góran Holm, Stephan Jeffferis, Bengt Broms, Fabrizio Leoni, Stefan Larsson, Minoru Aoi, and the late Renato Fiorotto.

Amongst organizations, FHWA were early supporters, while more recently DFI has been pivotal in organizing and running workshops, committees, and conferences.

And, of course, the dam community has directly contributed to the growth and development of DMM in the U.S. via its ownership of dams and levees that leak or can be damaged by earthquakes and storms.

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