A Brief History of Deep Mixing Methods

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

The first systematic studies of contemporary DMM 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 1970s, 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 United States. Developments in Japan and the Nordic countries seem to have 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.

The Nordic developments continued to focus on the use of dry reagents (cement and lime) and relatively light equipment, while the Japanese progressed into using fluid reagents (cement-based grouts) and heavier equipment for both marine and land-based projects. By 1986, there were a large number of proprietary (wet and dry) DMM systems in Japan, and a rapidly growing market already accounting for over 12,000,000 m^3 (16,000,000 yd^3) of ground treatment.

In retrospect, it is surprising that SMW Seiko's move to the U.S. was not replicated by Japanese contractors (e.g., Tenox, 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.

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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, Wyo. The DMM alternate was used principally to create an interlocking "honeycomb" of soilcrete columns, as well as a seepage cut-off. This project involved over 400,000 linear ft (120,000 linear m) of columns and was widely and justifiably publicized in the technical press.

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 to provide about 380,000 sf (37,200 m^2) of earth support walls at the Ted Williams Tunnel Approach in Boston, Mass. The industry learned much about the construction 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 1990s when about 550,000 cu yds (420,000 m^3) of soil were treated by a major JV 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, Calif.; the Islais Creek Sewerage Scheme, Ga.; the Marin Tower, Hawaii; the Lake Parkway, Wis.; and the LA Metro, Calif. By the late 1990s, the number of competitors grew, 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 Foundation Skanska, 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 Utah, (1997) and in San Francisco, Calif. (1998), Raito's wet DMM project at Woodrow Wilson Bridge, Va. (2000), and Hayward Baker's 350,000 cu yds (275,000 m^3) of dry, shallow mixing at Jewfish Creek, Fla., in 2005-2006.

Geo-Con had built a DMM cut-off wall through Lockington Dam, Ohio, and similar dam/levee cut-offs were installed in the early 1990s by Seiko and Raito, at projects such as Cushman Dam, Wash.; Lewiston, Idaho and Sacramento, Calif. However, the main application for DMM on hydraulic structures has been for seismic retrofit, and from the early 2000s onwards, major DMM installations had been recorded at Sunset North Basin Dam, Calif.; Clemson Upper and Lower Diversion Dams, S.C.; and San Pablo Dam, Calif., all by Raito. A landmark, full-scale test of various DMM (and other) techniques was conducted in 2006 by Treviicos at Tuttle Creek Dam, Kan., although the subsequent production works employed a slurry wall method.

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 its soft cohesive, organic soils. This field test, with 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. 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 one's 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.

Task Force Guardian was formed by the USACE and, by early 2006, DMM work, both wet and dry, was conducted on an emergency basis on four projects involving gate construction and levee remediation. In the following 4 years, 6 more projects were done under somewhat more relaxed conditions by the same two contractors — Hayward Baker (dry) and Raito (wet). These relatively modestly-sized projects were the forerunners for the massive LPV 111 project, an 8.8 km (5.5 mi) long component of the Lake Pontchartrain and Vicinity Hurricane Protection Scheme. This project involved over 1.3 million m^3 (1.7 million yd^3) of wet DMM, to improve the soft foundation soils, prior to the placement of over 0.8 million m^3 (1.1 million yd^3) of dry levee fill. The DMM was conducted principally by Treviicos (with contributions from Fudo

Construction) using its proprietary "Turbo Mix" system. Over 17,000 soilcrete elements were installed employing over 380,000 tonnes (417,000 tons) 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.

New Arrivals

All of the numerous vertical axis DMM techniques may be referred to as "conventional." As shown in Figure 1, 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. By 2011, over 150 projects were completed worldwide, mainly with Bauer's newly patented CSM, 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.

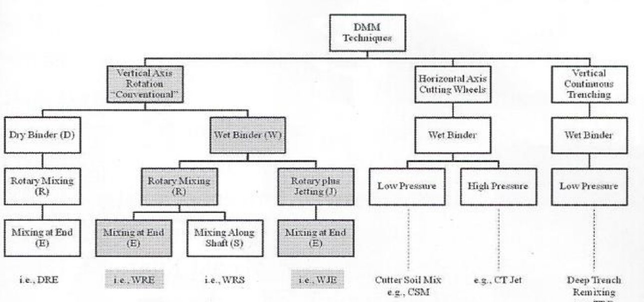

Figure 1. Classification of DMM technologies

The largest CSM project in the U.S. is the construction, by Bauer, of several miles of 600 mm (24 in) wide cut-off, to depths of over 20 m (65 ft) in Herbert Hoover Dike, Fla. In Canada, the current work being conducted by Golder Construction for foundation improvement at Kitimat, B.C., 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 solely 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. 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 (22 to 33 in) and depths to 55 m (180 ft) 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, Fla., for constructing miles of cut-off wall.

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 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 of different inorganic and organic soils; although more work remains to be done in this area. Designers and researchers in the U.S. have developed improved analysis techniques to permit efficient design against multiple failure modes and to successfully integrate design, construction and QC/QA to reliably 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 2000s by the National Deep Mixing Program, 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 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* (2013)
- *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, and San Francisco in 2013.

Landmark full-scale test of DMM techniques at Tuttle Creek, Kansas. The other four photos in this article are of the LPV-111 demonstration DMM project at Lake Ponchartrain, La., part of the USACE post- Katrina effort. 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.

The Way Forward

After 27 years of application in the U.S., DMM is, technologically speaking, in robust health. "Conventional" methods are continuously being modified by experienced 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 has 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 here.

In North America, one can cite, in no particular order, Brian Jasperse, 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, and Minoru Aoi.

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.