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Deep Mixing Method: A Global Perspective

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Abstract

Various types of contemporary Deep Mixing Method (DMM) techniques have been used in the United States since 1986. Such techniques owe their origins to Japanese and Scandinavian developments, which began almost three decades ago. The growing demands of urban infrastructure development and rehabilitation have created a very active and rapidly expanding market demand in the United States especially since the early 1990s, and there is a clear need for a new and fundamental review of the surprisingly large number of DMM techniques that are being used domestically, or are available in other parts of the world. Following a summary tracing the historical development of DMM, and a generic classification of applications, the paper provides a review of each of the many different proprietary methods, which the authors have identified during preparation of an international survey funded by the Federal Highway Administration (FHWA). Data are also provided on commercial aspects of the various DMM techniques worldwide.

Introduction

The Deep Mixing Method (DMM) encompasses a group of technologies that provide in situ soil treatment. Materials of various types, but usually of cementitious nature, are introduced and blended into the soil through hollow, rotated shafts equipped with

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cutting tools, and mixing paddles or augers that extend for various distances above the tip. The materials may be injected in either slurry (wet) or dry form. The treated soil or fill mass that results generally has a higher strength, lower compressibility and (usually) lower permeability than the virgin soil, although the exact properties obtained will reflect both the characteristics of the native soil, and the construction techniques and variables that are selected.

Although the original concept appears to have been developed in the United States in 1954, current practice reflects the intense efforts of researchers, backed by strong federal resources and demand, in both Japan and Scandinavia since 1967. During the last decade, however, domestic challenges to the specialty ground engineering community in the arenas of urban infrastructure development, seismic mitigation and environmental remediation, have led to a rapid growth in the use of such techniques in the United States also.

Recent international conferences, such as in Tokyo in 1996 and Logan, UT in 1997 have highlighted that there exist a surprisingly large number of different DMM techniques, each one typically proprietary to one, or a group of, specialty contractors. It is also clear that each technique has its own particular advantages and limitations, technically, logistically, and environmentally.

Given the rapid growth in the usage of DMM in the United States, it is therefore timely to present a global overview of these various different techniques so that they can be better understood by the engineering community and so more appropriately used. This paper first provides a summary of the historical evolution of DMM so that the reader can appreciate the lineage of the respective methods. It continues by briefly summarizing the main groups of applications, and comparing DMM with competitive methods in each category. The main focus of the paper, however, is the tabulation, within a new generic classification framework, of the different techniques, their characteristics, equipment, performance and so on. The paper concludes with a presentation of some commercial data relating to both domestic and international usage. Space restrictions prevent a more detailed review of treated soil properties, or a discussion of the advantages and disadvantages of DMM relative to alternative or competitive technologies. The interested reader is referred to the FHWA study (1998).

Historical Evolution

Table 1 provides a chronology of the major events in the ongoing development of the DMM techniques. It refers to a large number of these techniques by name, bearing in mind that the details of these techniques themselves are provided in Appendices 1 and 2. Table 1 highlights the commitment and energy of engineers in Scandinavia and Japan for over 30 years, initially pursuing similar paths, but soon following different directions in response to particular national demands. Also apparent is the

accelerating rate of progress in other regions, principally the United States and Western Europe, over the last 10 years.

Year	Event
1954	Intrusion Prepakt Co. (U.S.) develop the Mixed in Place (MIP) Piling Technique (single auger), and see sporadic use in the U.S., although widespread use continues in Japan till early 1970s.
1967	Port and Harbor Research Institute (PHRI, Ministry of Transportation, Japan) begin laboratory tests, using granular lime for treating soft marine soils (DLM). Research continued by Okumura, Terashi et al. through early 1970s to a) investigate lime-marine clay reaction and b) develop appropriate mixing equipment (U.C.S. of 0.1 to 1 MPa achieved) Early equipment used on first marine trial near Hareda Airport (10m below water surface).
1967	Laboratory and field researches begin on Swedish Lime Column method for treating soft clays under embankments using unslaked lime (Kjeld Paus, Linden - Alimak AB, in cooperation with Swedish Geotechnical Institute (SGI), EurocAB and ByggproduktionAB).
1974	PHRI report that the Deep Lime Mixing method (DLM) has commenced full scale application in Japan. First applications in reclaimed soft clay at Chiba. (DLM continues to be popular until late 1970s when CDM and DJM supersede it.)
1975	Following researches from 1973 to 1974, PHRI develop the forerunner of the Cement Deep Mixing method (CDM) using cement grout and employ it for the first time in large scale projects in soft marine soils offshore. (Original variants include DCM, CMC (still in use from 1974), then DCCM, DECOM, Demic, etc.)
1976	Public Works Research Institute (PWRI) (Ministry of Construction, Japan) begins researches on the Dry Jet Mixing method (DJM) using dry powdered cement (or less commonly, quick-lime); "first practical stage" completed in late 1980. Representatives of PHRI also participate.
1976	SMW method used commercially for first time in Japan.
1977	First "practical use" of CDM in Japan (marine and land uses).
1980	First commercial use in Japan of DJM (land use only).
1981	Prof. Mitchell presents General Report at ICSMFE in Stockholm on lime-cement columns.
1985	SGI (Sweden) publishes 10 year progress review. (Åhnberg and Holm).
1986	SMW Seiko Inc. commence operations in U.S. under license from Seiko Kogyo.
1987 - 1988	SMW method used in massive ground treatment and improvement program for seismic retrofit at Jackson Lake Dam, WY.

Table 1. Highlights of Historical Development of DMM (continues).

Year	Event
1988 - 1989	Development by Geocon, Inc. in U.S. of DSM (Deep Soil Mixing) and SSM (Shallow Soil Mixing) techniques.
1989	Start of exponential growth in use of Lime Cement Columns in Sweden and Finland.
1992 - 1994	SMW method used for massive earth retention and ground treatment project at Logan Airport, Boston.
1992 - 1993	First SCC installation in U.S. (Richmond, CA).
1993	CDM and DJM Research Institutes publish Design and Construction Manuals (in Japanese).
1994	First commercial application of original Geojet system in the U.S. (Texas) following several years of development by Brown & Root.
1995	Swedish government sets up new "Swedish Deep Stabilization Research Center" at SGI (1995-2000: $8 -10 M): "Svensk Djupstabilisering". Consortium includes owners, Government, contractors, universities, consultants, research organizations, co-coordinated by Holm of SGI.
1995	Finnish government sets up new research consortium for the ongoing Road Structures Research Programme ("TPPT") - till 2001.
1995	Swedish Geotechnical Society publishes new design guide for lime and lime-cement columns (P. Carlsten).
1996	SGI (Sweden) publish 21-year experience review.
1996	First commercial use of lime columns in the U.S. (by Stabilator in Queens, NY).
1996 - 1997	Hayward Baker install 1.2 to 1.8m diameter columns for foundations, earth retention and ground improvement.
1997	SMW method used for huge soil treatment project at Fort Point Channel, Boston, MA (Largest DMM project to date in North America), and other adjacent projects. Input at design stage to U.S. consultants by Dr. Terashi (Japan).
1997	First commercial use in U.S. of modified Geojet system (by Condon Johnson Associates at San Francisco Airport, CA).
1997	Major lime-cement column application (I-15, Salt Lake City) proposed by Swedish contractor, Stabilator.
1997	Raito Kogyo (Japan) establish U.S. subsidiary in California.
1997 - 1998	Master Builders Technologies develop families of dispersants for soil (and grout) to aid DMM penetration and mixing efficiency.

Table 1. Highlights of Historical Development of DMM (concluded).

Applications and Applicability of DMM

Six basic groups of applications can be identified for contemporary deep mixing methods:

1. Hydraulic cutoffs: DMM walls to prevent water movement through or under water retaining structures, such as dams or levees (e.g., Sacramento, CA) and into deep basements excavated below the water table.
2. Structural walls: DMM walls containing steel elements to resist lateral earth pressures in the construction of deep excavations, such as for cut and cover tunnels (Ted Williams Tunnel, Boston, MA) and deep basements.
3. Ground treatment: Block treatment to strengthen in a uniform manner large volumes of foundation soil in conjunction with deep excavations (Fort Point Channel, Boston, MA), and structural foundations.
4. Ground improvement: Discrete DMM elements (columns or panels) used as reinforcing elements to improve the overall performance of large, compressible soil masses under relatively lightly loaded structures, such as road (e.g., I-15, UT) or railway embankments.
5. Liquefaction mitigation: Interlocking DMM box or cellular structures to reduce the tendency for mass liquefaction and lateral spreading during seismic events under large embankments (e.g., Jackson Lake Dam, WY) or buildings.
6. Hazardous materials: DMM walls to contain, or DMM block treatment to fix, environmentally unacceptable materials.

Classification of Methods

A generic classification of the numerous methods used internationally can be made on the following simple basis:

- Is the cementitious material injected in a slurry or wet (W) form, or in a dry (D) state?
- Is this binder mixed with the soil via rotary energy only (R) or is the mixing enhanced/ facilitated by high pressure jet (J) grout type methods?
- Is the mixing action only occurring near to the drilling tool (E), or is it continued along the shaft (S) for a significant distance above it, via augers and/or paddles?

The classification shown on Figure 1 has therefore been developed by the authors, and four categories of methods - WRS, WRE, WJE and DRE - have been identified. No methods have been found in the DRS, DJE, or DJS categories since dry injection methods only feature end mixing with relatively low pressure binder injection pressures via compressed air, and jetted methods only feature end mixing (hence no WJS).

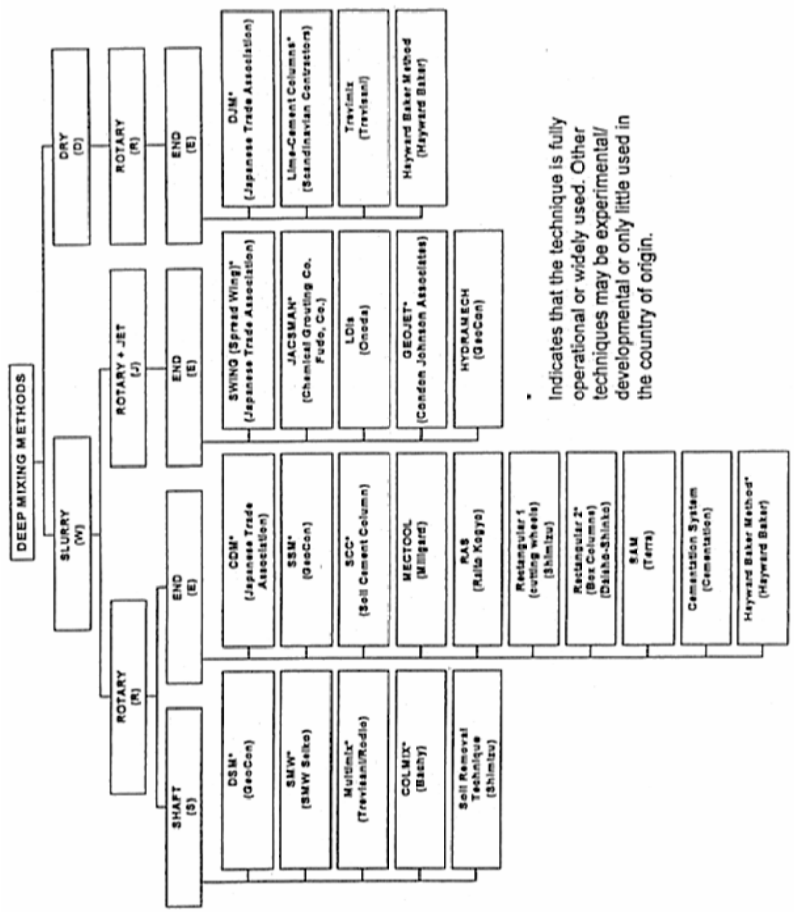

Figure 1. Classification of DMM techniques.

Features of Methods

The FHWA Report (1998) provides extensive data on each of the methods identified in Figure 1. Space restrictions prevent more than a brief summary of the more significant methods being provided in this publication (Appendices 1 and 2). The following general points must be borne in mind while considering these data:

- New methods, refinements of existing methods, and developments in materials (e.g., use of flyash, gypsum and slag in slurries; clay dispersants to aid penetration and improve mixing efficiency) are continually underway.
- As noted by Taki and Bell (1997), the technical goal of any DMM technique is to provide a uniformly treated mixed body, with no discrete lumps of binder or soil, a uniform moisture content, and a uniform distribution of binder throughout the mass. The most important requirements for installation are therefore: thorough and uniform mixing of the soil and binder; appropriate water/cement ratio; and appropriate grout injection ratio (e.g., volume of grout: volume of treated soil).
- The table includes methods not conventionally or nationally regarded as DMM, for example, the SMW Method (used only for walls in Japan), while the Scandinavian practitioners do not conventionally address their Lime-Cement Column Method as DMM.
- Despite their generic similarity, there are major and significant regional and procedural variations. For example, unconfined compressive strengths (U.C.S.) of treated soil using WRE, WRS, and WJE are typically higher than 1 MPa, except (e.g., FGC-CDM) where lower strengths are deliberately engineered. For DRE methods in Japan (e.g., DJM) a minimum U.C.S. of 0.5 MPa is obtained, whereas for the comparable DRE Scandinavian method (Lime-Cement Columns), rarely are strengths in excess of 0.15 MPa designed and/or achieved. Furthermore, treated soils in Scandinavia may be considered as providing vertical drainage, whilst similar soils in other countries, by other methods, may be regarded as relatively impermeable.
- Table 2 (Terashi, 1997) summarizes the factors influencing the strength of treated soil. In laboratory testing, there is no way to simulate factors III and IV except for the amount of binder and the curing time. Thus laboratory testing features standardization of these factors, and so it must be realized that the strength data provided by such tests is "not a precise predication" (Terashi, 1997) but only an "index" of the actual strength. Field testing is essential, and invariably appears to provide, for a number of reasons, inferior and more variable strength data.
- Deep mixing is, of course, not a panacea for all soft ground treatment, improvement, retention and containment problems, and in different applications it can be more or less practical, economic or preferable than competitive technologies. In the most general terms, DMM may be most attractive in projects where the ground is neither very stiff nor very dense, nor contains boulders or other obstructions; to depths of less than about 30m;

where there is relatively unrestricted overhead clearance; where a constant and good supply of binder can be assured; 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; or where treated ground strengths have to be closely engineered (typically 0.1 to 5 MPa). Otherwise, and depending always on local conditions, it may prove more appropriate to use jet grouting, diaphragm walling, sheet piling, caissons, beams and lagging, driven piles, wick drains, micropiles, soil nails, vibrodensification, compaction grouting, deep dynamic consolidation, bioremediation, or vapor extraction.

- The materials injected are tailored to the method used, their local availability, the ground to be treated and the desired or intended result. Generally, for the methods using a fluid grout, the constituents include cements, water, bentonite, clay, gypsum, flyash, and various additives. Water cement ratios typically range from less than 1 to over 2, although the actual in place w/c ratio will depend on any "predrilling" activities with water, or other fluids. Most recently, dispersants (Gause, 1997) can be used, both to breakdown cohesive soils, and also to render more efficient the grout injected. For dry injection methods, cement and/or unslaked lime are the prime materials used.
- For wet methods (mechanically simpler and so preferable in "difficult" geographic locations), the cement injected is typically in the range of 100 to 500 kg per cubic meter of soil to be treated. The ratio of volume of fluid grout injected to soil mass treated is typically about 20 to 40%. (A lower injection ratio is preferable, to minimize cement usage and spoil).
- For dry methods, (in soils of 60 to over 200% moisture content), typically 100 to 300 kg of dry materials per cubic meter of treated soil are used, providing strengths of 0.2 to 20 MPa, depending very much on soil type (low strengths and solids contents in Scandinavia), with minimal spoil or heave potential.
- Treated soil properties (recalling that cohesive soils require more cement to give equivalent strengths than cohesionless soils) are usually in the ranges shown in Table 3.
- It must be remembered that different techniques are intended specifically to provide higher strengths, or lower permeabilities and so the figures cited above are gross ranges only, and that the data provided by the individual corporations supersede those presented above for specific applications.

I	Characteristics of hardening agent	
	1.	Type of hardening agent
	2.	Quality
	3.	Mixing water and additives
II	Characteristics and conditions of soil (especially important for clays)	
	1.	Physical chemical and mineralogical properties of soil
	2.	Organic content
	3.	pH of pore water
	4.	Water content
III	Mixing conditions	
	1.	Degree of mixing
	2.	Timing of mixing/re-mixing
	3.	Quality of hardening agent
IV	Curing conditions	
	1.	Temperature
	2.	Curing time
	3.	Humidity
	4.	Wetting and drying/freezing and thawing, etc.

Table 2. Factors affecting the strength increase (Terashi, 1997).

U.C.S.	0.2 - 5.0 MPa (0.5 - 5 MPa in granular soils) (0.2 - 2 MPa in cohesives)
k	10^{-6} - 10^{-9} m/s (lower if bentonite is used)
E	350 to 1000 times U.C.S. for lab samples and 150 to 500 times U.C.S. for field samples
Shear strength (direct shear, no normal stress)	40 to 50% of U.C.S. at U.C.S. values < 1 MPa, but this ratio decreases gradually as U.C.S. increases.
Tensile strength	Typically 8 - 14% U.C.S.
28-day U.C.S.	1.4 to 1.5 times the 7-day strength for silts and clays 2 times the 7-day strength for sands
60-day U.C.S.	1.5 times the 28-day U.C.S., while the ratio of 15 years to 60 days U.C.S. may be as high as 3 to 1. In general, grouts with high w/c ratios have much less long term strength gain beyond 28 days, however.

Table 3. Typical data on soil treated by deep mixing.

Commercial Aspects

In the United States, there are at least nine companies who offer, or claim to offer, deep mixing services. Four (GeoCon, Condon Johnson, Terra, and Millgard) appear to have no links with foreign ownership or licensees, having developed their own systems. The others (Hayward Baker, Raito, Seiko, Stabilator, and SCC) are either U.S. operations with foreign ownership or use methods under foreign license. Based on the authors' investigations, it would seem that from 1986 to 1992, the annual value of deep mixing work conducted was in the range of $10 to 20 million, increasing by over 50 percent to 1996. Since then, as a result of massive works in Boston, Salt Lake City and the West Coast, this annual volume is probably now in the range of $50 to 80 million. For DMM used in environmental applications, the annual market may be around $20 to 30 million, increasing at about 5 to 10 percent annually.

Large scale systems may cost $80,000 to $200,000 to mobilize (much lower for methods such as Lime-Cement Columns). Typical prices for treatment are $100 to 250/m^2, or $50 to 100/m^3.

In Japan, the CDM Association claims to have treated over 26 million m^3 of soil from 1977 to 1995 (30 percent in the period 1992 to 1995) with about 60 percent being offshore (Figure 2). The DJM Association records 16 million m^3 of soil treatment from 1980 to 1996, involving 2345 separate projects, and an annual volume now approaching 2 million m^3 (Figure 3). By 1994, SMW Seiko, referring to their deep mixing wall system, had recorded 4,000 projects worldwide for a total treatment of 12.5 million m^2 (7 million m^3).

In Scandinavia, Åhnberg's data (Figure 4) illustrate the rapid growth in Swedish applications, while similar data illustrate a strong but smaller and steadier market in Finland (about 250,000 m^3 per year, 80 percent of which is lime-cement columns.) Markets in Norway and the Baltic countries are much smaller but have considerable growth potential. Selling prices in Scandinavia are typically in the range of $7 to 12/lin. m.

Similar data have not been found for other European countries, but there is no evidence that levels of activity in countries like U.K., France, Germany and Italy currently approach those in the U.S.

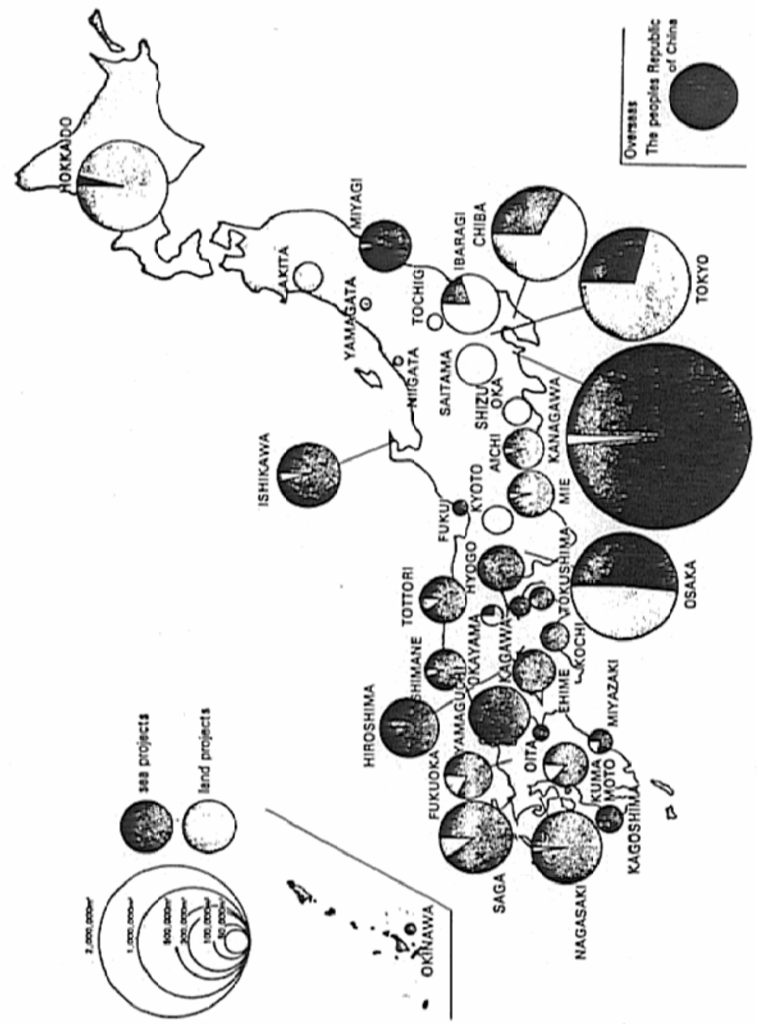

Figure 2. Data on use of CDM in Japan and China till 1993 (CDM Association, 1994).

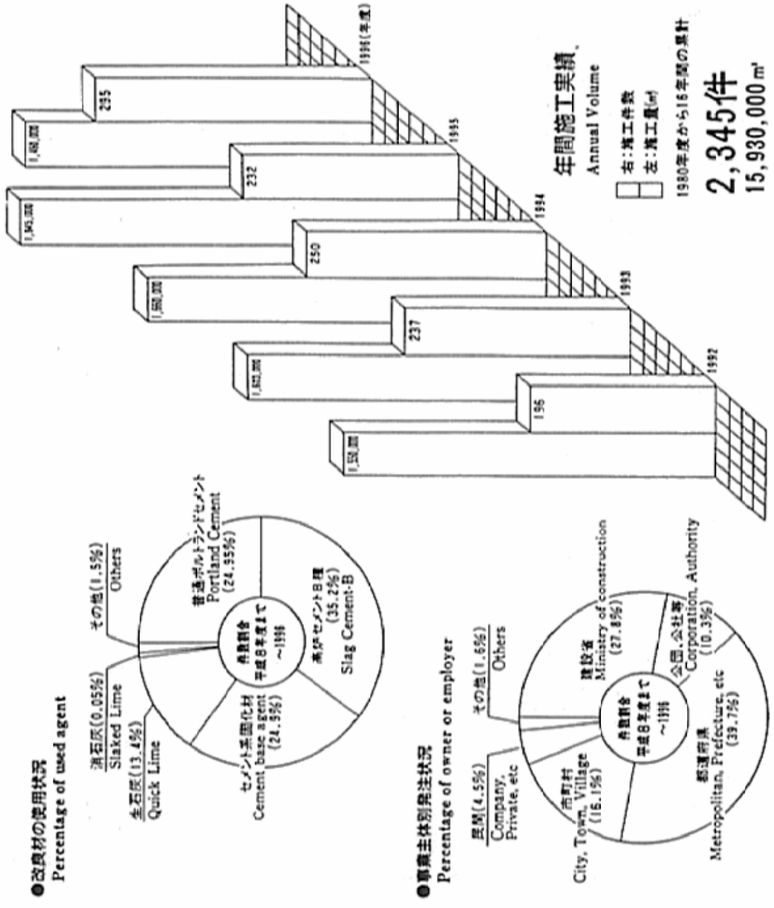

Figure 3. Data on DJM usage in Japan. Left bar represents volume (m^3) and right bar represents number of projects (DJM Association, 1996).

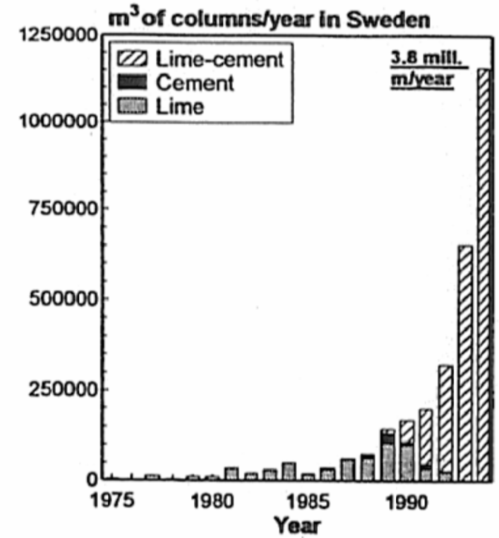

Figure 4. Use of different stabilizing agents for deep stabilization of soils in Sweden 1975-1994 (Åhnberg, 1996).

Final Remarks

Deep mixing is one of the world's most attractive and fastest growing specialty geotechnical construction processes. It offers solutions in a wide range of applications, in softer soils to moderate depths. Levels of knowledge and expertise are exceptionally high in Scandinavia and Japan, and rapidly improving in North America, where its technical and commercial potential is now becoming fully recognized. It is hoped that this paper will provide a structured introduction to the many techniques and systems that currently exist and a basis for understanding the innovations that will doubtless follow in quick order.

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Classification Name Company Geography	WRS DSM GeoCon N. America	WRS SMW SMW Seiko S.E. Asia, U.S.
General Description of Method	Adjacent discontinuous augers rotate in alternate directions. Most of grout injected mainly on downstroke	Adjacent discontinuous augers rotate in alternate directions. Water air or grout used on downstroke and grout on upstroke
Special Features/Patented Aspects	Lower 3m usually double stroked. Strong QA/QC by electronic methods	Special electric head patented Double stroking "oscillation" common especially in cohesive soils. Discontinuous auger flights are positioned at intervals to reduce torque requirements.
Details of Installation Shafts Diameter Depth RPM Productivity/output	1-4, usually 4 0.6 to 1.0m, usually 0.8m 35m 20 - 50 0.6 m/min penetration 2 m/min withdrawal/mixing	1-5, usually 3 0.55 to 1.5m, usually 1m 60m claimed, 35m practical 15-20 0.5 m/min penetration 2 m/min withdrawal/mixing 100-200 m^3 per shift i.e., 100-250 m^2 per shift
Mix Design *(depends on soil type and strength requirements)* Materials w/c ratio Cement ratio (k_{cement}/m^3_{soil}) Volume ratio($Vol_{grout}:Vol_{soil}$)	Cement grout ± bentonite and other additives w/c = 1.2-2.5 300-500kg/m^3 soil 30-40%	Cement grout ± bentonite and other additives w/c = 1.3-2.5 250-750 kg/m^3 soil 50-100%
Reported Treated Soil Properties U.C.S. k E	0.3-7 MPa (clay strengths approx. 40% those in sands) 1×10^{-8} - 1×10^{-9} m/s 500 to 1350 x U.C.S.	0.3-1.3 MPa (clay) 1.4-4.2 MPa (sands) 1×10^{-7} - 1×10^{-10} m/s 500 to 1350 x U.C.S.
Specific Relative Advantages and Disadvantages	Economic, proven systems Mixing efficiency can be poor in stiff cohesives Can generate large spoil volumes	
Notes	Developed in late 1980s	Developed in 1972: first used 1976 in Japan, 1986 in U.S.
Representative References	Ryan and Jasperse (1989, 1992) Day and Ryan (1995)	Taki and Yang (1989, 1991) Yang (1997)

Appendix 1. Details of major fully operational deep mixing techniques (continues).

Classification Name Company Geography	WRS Trevimix (Multimix) Trevisani, Rodio Italy	WRE CDM 48 members of CDM Association Japan, China
General Description of Method	Adjacent augers rotate in opposite directions. Grout injected during penetration. Prestroked with water in clays. Auger rotation reversed during withdrawal. Mixing occurs over 8-10m length of shaft.	Shafts have 4-6 mixing blades above cutting tool. Grout injected mainly during penetration. Also a 2 min mixing period at full depth.
Special Features/Patented Aspects	Pre-drilling with water ± additives in very resistant soils. Process is patented by Trevisani	Comprises numerous subtly different methods all protected under CDM Association
Details of Installation Shafts Diameter Depth RPM Productivity	1-3, typically 3 550-800mm at 450-600mm spacings 25m 12-30 0.35-1.1 m/min penetration 0.48-2 m/min withdrawal	2-8m (marine): 1-2m (land) 1-2m (marine): 0.7-1.5 (land) 70m (marine): 40m (land) 20-30 (penetration):60 (withdrawal) 0.5-2 m/min (avg. 1/m/min) 1-2 m/min (withdrawal) (1000 m^3/shift for marine; 100-200 m^3/shift on land)
Mix Design *(depends on soil type and strength requirements)* Materials w/c ratio Cement ratio (k_{cement}/m^3_{soil}) Volume ratio ($Vol_{grout}:Vol_{soil}$)	Cement, water mainly plus bentonite used in clays, additives common Typically low, i.e., 0.6-1.0 200-250 kg/m^3	Wide range of materials including cement, bentonite, gypsum, flyash 0.6-1.3 (usually low) 100-200 kg/m^3 15-30%
Reported Treated Soil Properties U.C.S. k E	0.5-5 MPa (sands) 0.2-1 MPa (silts, clays) < 1×10^{-7} m/s	Strengths can be closely controlled by varying grout composition from < 0.5-4 MPa 10^{-8} - 10^{-9} m/s 350-1000 x U.C.S.
Specific Relative Advantages and Disadvantages	Goal is to minimize soil removal (10-20%) and enhance mixing efficiency	Vast amount of R&D information available. Specifically developed for softer marine deposits and fills
Notes	Developed jointly in late 1980s	Association founded in 1977 Research initiated under Japanese Government (1967). Offered in the U.S. by Raito.
Representative References	Pagliacci and Pagotto (1994)	CDM (1996) Okumura (1996)

Appendix 1. Details of major fully operational deep mixing techniques (continues).

Classification **Name** **Company** **Geography**	WRE SCC SCC Technology SCC (U.S.A.): Tenox (Japan)	WRE HBM Hayward Baker Inc: A Keller Co. (U.S.A. but with opportunities for sister companies worldwide)
General Description of Method	Grout is injected during penetration. A non-rotated "share blade" is located above tip. At target depth, 1 minute of additional injection plus oscillation for 1.5-3m Withdrawal with counter rotation	Grout injected during penetration followed by 5 minutes mixing and oscillation at full depth, and rapid extraction with injection of "backfill grout" only (1-5% total)
Special Features/Patented Aspects	Very thorough mixing via "share blade" action which is patented.	Method proprietary to Keller.
Details of Installation		
Shafts	Single with 3 rotated mixing blades plus "share blade"	Single with 2 or 3 pairs of paddles
Diameter	0.6m	1.2-2.6m, typically 2.1m
Depth	18m max	15m max
RPM	30-50	20-25 (penetration): higher upon withdrawal
Productivity	1 m/min in and out	0.3-0.5 m/min (penetration): faster upon withdrawal. In excess of 500 m^3/shift
Mix Design *(depends on soil type and strength requirements)* Materials	Typically cement, but others e.g., ash, bentonite possible.	Varied in response to soil type and needs
w/c ratio	0.6 (clays) to 1.0 (sands)	1-2
Cement ratio (k_{cement}/m^3_{soil})	100-450 kg/m^3 cement	150 kg/m^3 cement
Volume ratio ($Vol_{grout}:Vol_{soil}$)	30-35%	15-30%
Reported Treated Soil Properties U.C.S.	3.5-7 MPa (sands) 1.3-7 MPa (cohesives)	3-5-10 MPa (sands) 0.2-1.4 MPa (clays)
k	10^{-8} m/s	10^{-10} m/s
Specific Relative Advantages and Disadvantages	Low spoil with minimal cement loss claimed, due to low w/c and minimized injected volume	Good mixing: moderate penetration: low spoils volume
Notes	Used since 1979 in Japan and 1993 in U.S.A.	Developed since 1990
Representative References	Taki and Bell (1997)	Burke et al. (1996)

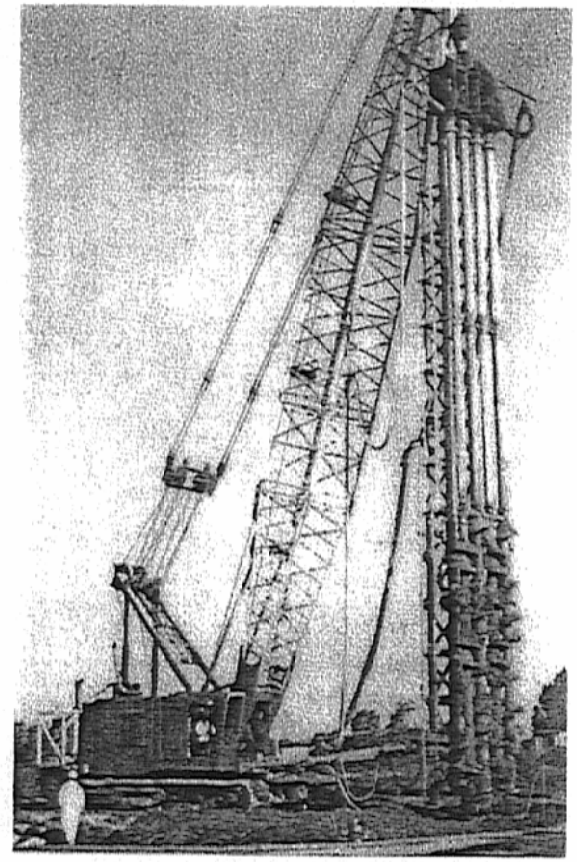
Appendix 1. Details of major fully operational deep mixing techniques (continues).

Classification **Name** **Company** **Geography**	WJE JACSMAN Chemical Grout Co., Fudo Co. Japan	WJE GeoJet Condon Johnson Associates Western U.S.A.
General Description of Method	Grout injected at low pressure via blades during penetration. During withdrawal, obliquely inclined jets are used at high pressures to increase diameter and enhance mixing efficiency	Grout is jetted via ports on a pair of wings during penetration
Special Features/Patented Aspects	The combination of DM and jet grouting ensures good joints between adjacent columns, and columns of controlled diameter and quality. Column formed is 1.9m x 2.7m in plan. Patented process.	Combination of mechanical and hydraulic cutting/mixing gives high quality mixing and fast penetration. Licenced by CJA.
Details of Installation		
Shafts	2 shafts each with 3 blades.	1 shaft with pair of wings
Diameter	1m (blades at 0.8m spacing)	400-1200mm
Depth	20m	40m max (20m typical)
RPM	20	150-200 (recent developments focusing on slower rpm)
Productivity	1 m/min penetration 0.5-1 m/min withdrawal	2-12 m/in (penetration) 10 m/min (withdrawal) 150m of piles/hr possible
Mix Design *(depends on soil type and strength requirements)* Materials	Cement	Cement, additives
w/c ratio	1.0	1.0
Cement ratio (k_{cement}/m^3_{soil})	200 kg/m^3 (jetted) 320 kg/m^3 (DM)	570 kg cement/m of column (typical)
Volume ratio ($Vol_{grout}:Vol_{soil}$)	Air also used to enhance jetting 200 l/min per shaft during DM penetration 300 l/min during withdrawal (jetting)	30-40%
Reported Treated Soil Properties U.C.S.	1-6 MPa (silty sand and clay)	4.8-10.3 MPa (clay)
Specific Relative Advantages and Disadvantages	New system combining DM and jet grouting principles to enhance volume and quality of treatment	Computer control of penetration parameters excellent. High strength. Low spoil volumes. Excellent mixing.
Notes	Name is an acronym for Jet and Churning System Management. Not yet fully operational	Developed since early 1990s. Fully operational in Bay Area.
Representative References	Miyoshi and Hirayama (1996)	Reavis and Freyaldenhoven (1994)

Appendix 1. Details of major fully operational deep mixing techniques (continues).

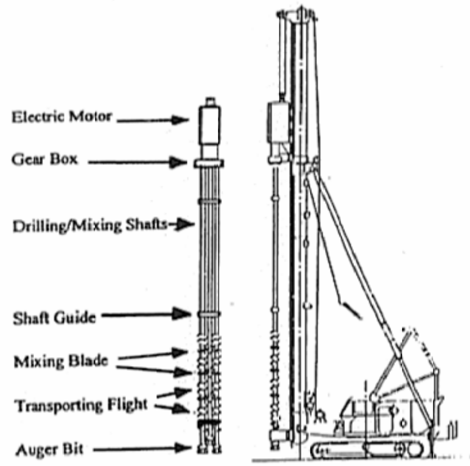
Classification **Name** **Company** **Geography**	DRE Dry Jet Mixing DJM Association (64 companies) Japan	DRE Lime-Cement Columns Various (Scandinavia and Far East); Stabilator (U.S.A.) Scandinavia, Far East, U.S.A.
General Description of Method	Soil is penetrated while injecting compressed air from the lower blades. Dry materials are injected during withdrawal via compressed air, and reverse rotation.	Soil is penetrated while injecting compressed air below mixing tool. Dry materials are injected during withdrawal via compressed air, and reverse rotation.
Special Features/Patented Aspects	System is patented and protected by DJM Association. Two basic patents (blade design and control system)	Very low spoil. High productivity. Efficient mixing. Patents are held by the contractors. Strong reliance on computer control.
Details of Installation Shafts Diameter Depth RPM Productivity	1-2 shafts spaced at 0.8 to ~1.5m, each with 2 pairs of blades 1m 33m max 5-50 typically 50-55 mins for 9m column 0.5-3 m/min withdrawal	Single shaft, various types of cutting/mixing blades. 500-1200mm, typically 600, 800mm 25m max 100-200, usually 130-170 0.6-0.9 m/min (withdrawal) 400-1000 lin m/shift
Mix Design *(depends on soil type and strength requirements)* Materials Cement ratio (k_{cement}/m^3_{soil})	Usually cement, but quicklime in clays of very high moisture contents 100-200 kg/m³ Range is 100-500 kg/m³ but typical is 100-300 kg/m³	Cement and lime in various percentages (typically 50:50 or 75:25) 23-28 kg/m (600mm diameter); 40 kg/m (800mm diameter) i.e., 80-150 kg/m³
Reported Treated Soil Properties U.C.S.	Greatly varies depending on soil and binder, 1-10 MPa	Varies but typically 0.2-0.3 MPa (0.2-2 MPa, possible)
Specific Relative Advantages and Disadvantages	Very little spoils; efficient mixing. Great deal of R&D experience.	Same as for DJM. Excellent Swedish/Finnish research continues.
Notes	Developed by Japanese Government and fully operational in 1980. Offered in the U.S. by Raito.	Developed by Swedish industry and Government, with first commercial applications in mid 1970s.
Representative References	DJM Brochure (1994); Fujita (1996)	Holm (1994); Rathmeyer (1996)

Appendix 1. Details of major fully operational deep mixing techniques (concluded).

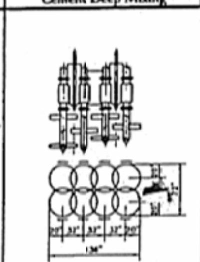
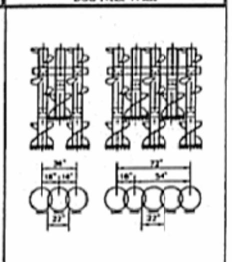


DSM system (Courtesy: GeoCon, Inc.)

Appendix 2. Illustrations of various deep mixing methods described in Appendix 1 (continues).

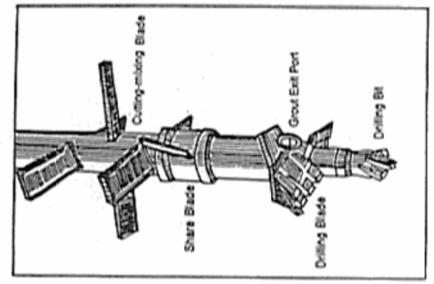


Schematic of SMW system (Taki and Bell, 1997).

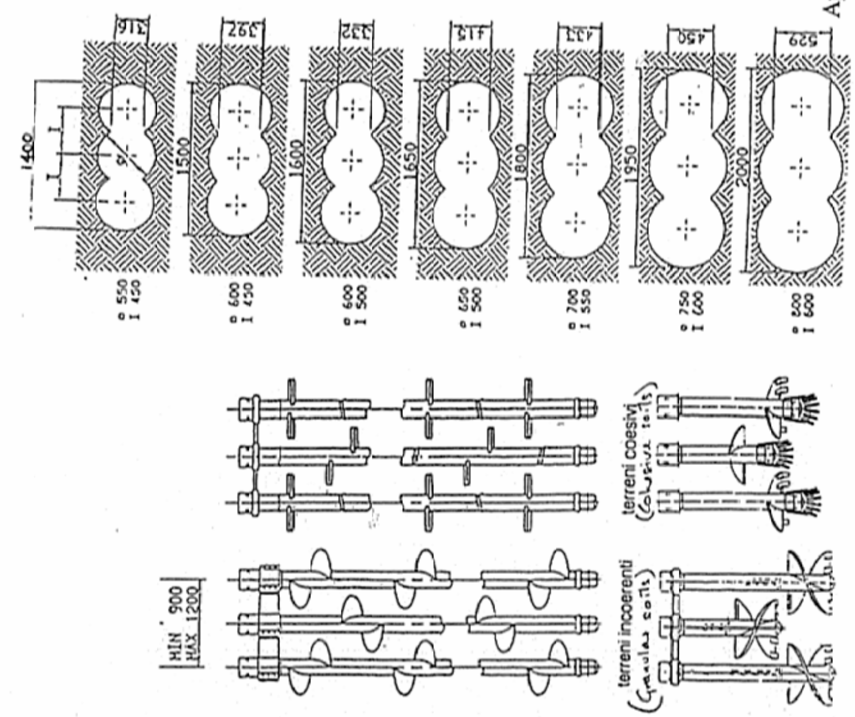
Title	CDM Cement Deep Mixing	SMW Soil Mix Wall
Sketches of Repre-sentative Mixing Mechan-isms	 ø = 39" to 63" available 1 ft = 0.305 m	 ø = 22" to 40" available 1 ft = 0.305 m
Descriptions	Rotation of multiple axis shafts create relative movement and shear in soil for soil-reagent mixing.	Uses multiple auger, paddle shafts rotating in alternating directions to mix in situ soil with cement grout or other reagents to form continuous soil-cement walls.

Comparisons of SMW and CDM shaft arrangements (Yang, 1997).

Appendix 2. Illustrations of various deep mixing methods described in Appendix 1 (continues).

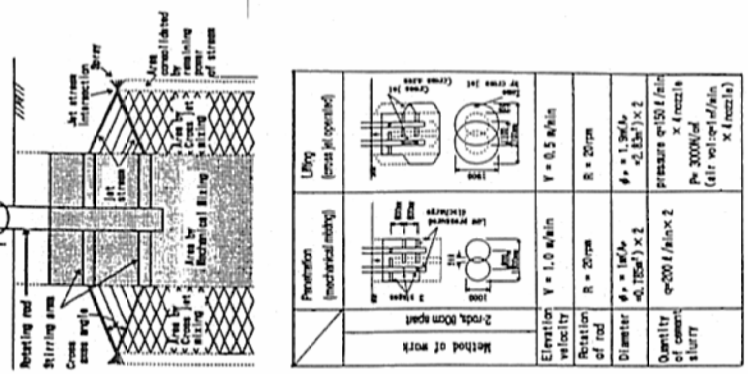


Details of SCC mixing tool (above) (Taki and Bell, 1997).

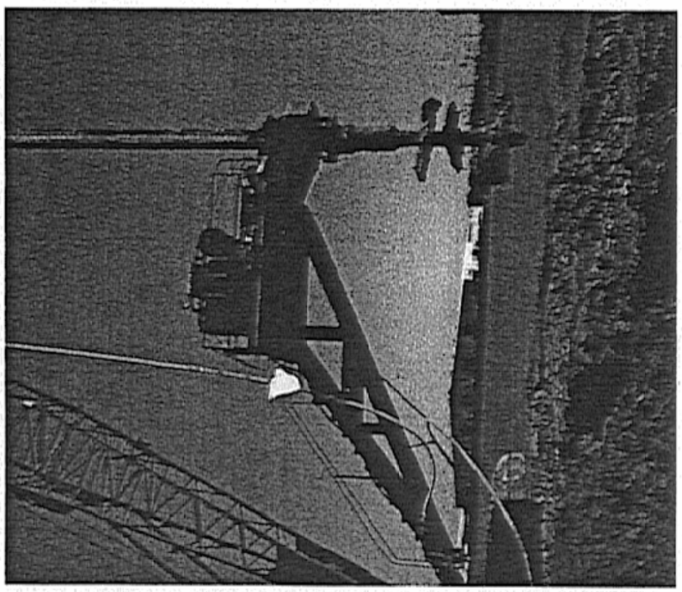


Details of Multimix (left) (Courtesy: Rodio)

Appendix 2. Illustrations of various Deep Mixing Methods described in Appendix 1 (continues).

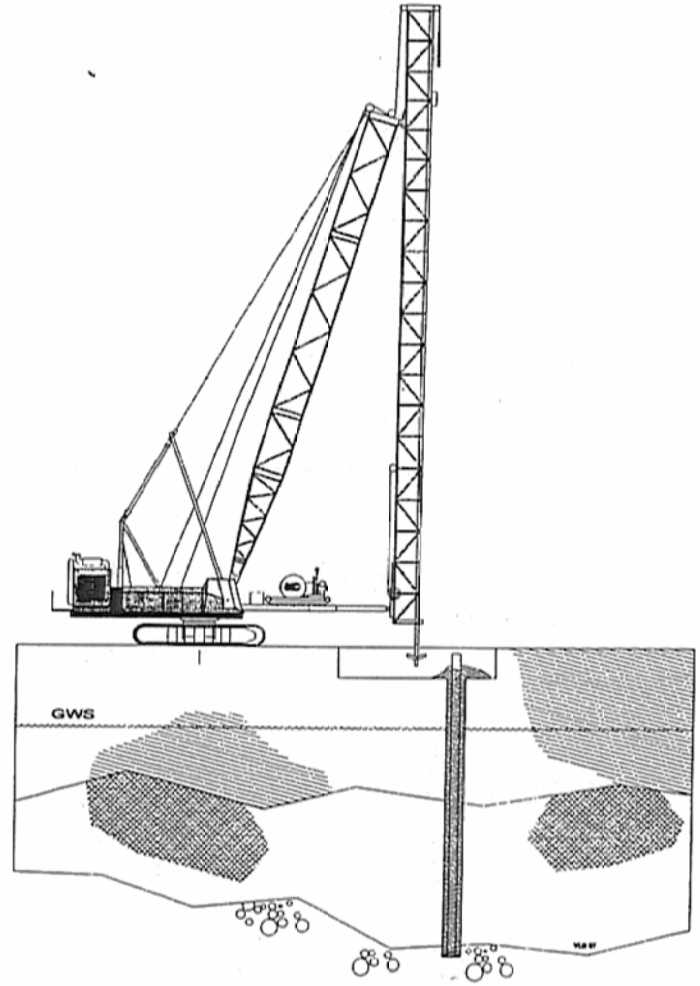


Details of JACSMAN system
(Miyoshi and Hirayama, 1996)



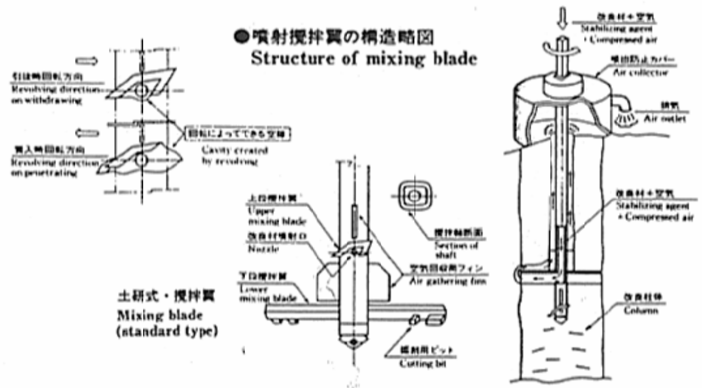
HBM tooling
(Courtesy: Hayward Baker, Inc.)

Appendix 2. Illustrations of various Deep Mixing Methods described in Appendix 1 (continues).

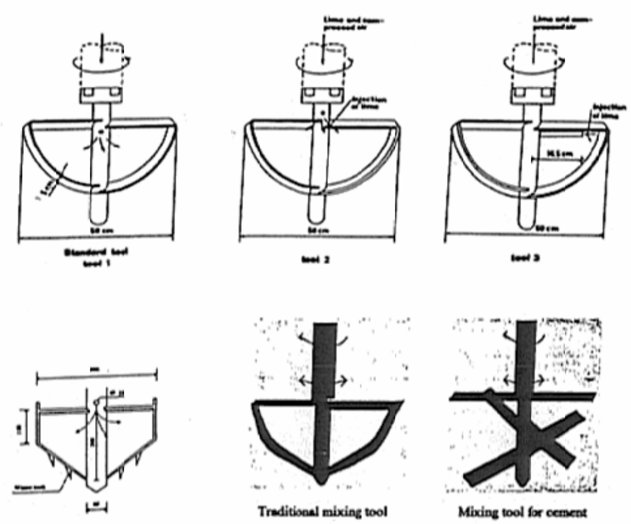


GeoJet system (Courtesy: Condon Johnson Associates).

Appendix 2. Illustrations of various deep mixing methods described in Appendix 1 (continues).



Details of DJM system (DJM Association, 1994).



Details of mixing tools for Lime-Cement Columns (Courtesy: Stabilator).

Appendix 2. Illustrations of various deep mixing methods described in Appendix 1 (concluded).