An Introduction to the Deep Soil Mixing Methods as Used in Geotechnical Applications

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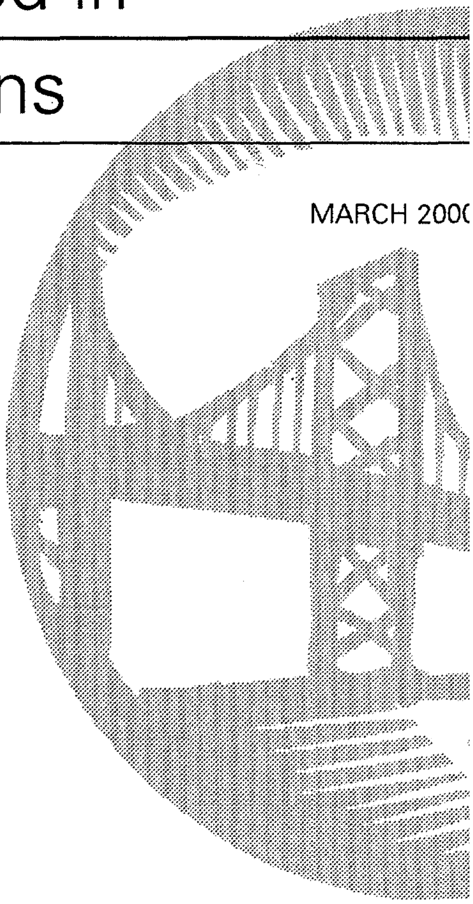

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report documents a study of various Deep Mixing Methods (DMM). Included is a historical survey of the method, an applications summary, a comparison with other competing methods for soil treatment, and a consideration of markets for the method worldwide. The report should be of interest to engineers and technologists working in the fields of deep soil excavations and the improvement of soft soil foundations to support heavy loads.

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Director, Office of Infrastructure
Research and Development

NOTICE

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16. Abstract

The Deep Mixing Method (DMM) is an in situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. This report first traces the historical development of the various propriety DMM methods and provides a structured summary of applications. It also compares the applicability of DMM with other competitive forms of ground treatment and improvement. The bulk of the report constitutes a description of the individual methods, focusing on the equipment, the procedures, and the properties of the treated soil. The report continues by describing the nature of the market in North America, Japan, and Scandinavia, while observations are also made on the various potential barriers to further growth in the United States. This report incorporates some factual data from an earlier Federal Highway Administration (FHWA) draft report (1996), but follows a different structure and philosophy.

This volume is the first in a series. The other volumes in the series are:

FHWA-RD-99-144 Volume II: Appendices
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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ACKNOWLEDGMENTS

The data contained in this report are derived from two sources: the published technical papers and trade brochures listed in the references, and personal communications from many specialists in the technique, both in the United States and overseas. These specialists have reviewed and contributed to successive drafts over a period of 2 years. In addition, the report has identified 24 different deep mixing techniques worldwide. Of these, the details of 18 have been further peer reviewed by representatives of the companies who conduct the particular technique, including all those who operate in the United States. The authors very much appreciate the input from these reviewers, who include:

Greg Aluce (Layne Christensen Company)
George Burke (Hayward Baker, Inc.)
Ed Cardoza (Millgard Corporation)
Nino Catalano (Trevi-ICOS)
Jerry DiMaggio (FHWA)
Al DiMillio (FHWA)
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Mel Esrig (Stabilator)
Chris Gause (Master Builders Technologies)
Frank Grynkewicz (Goldberg Zoino & Associates, Inc.)
Dan Himick (Modern Continental)
Goran Holm (Swedish Geotechnical Institute)
James Johnson (Condon Johnson Associates, Inc.)
James Lambrechts (Haley & Aldrich, Inc.)
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Mark Meyers (U.S. Army Corps of Engineers)
Pete Nicholson (GeoCon, Inc.)
Tom O'Rourke (Cornell University)
Jason Page (Condon Johnson Associates, Inc.)
Seth Pearlman (Nicholson Construction Company)
Lonnie Schellhorn (GeoJet)
Osamu Taki (SCC Technology, Inc.)
Masaaki Terashi (Nikken Sekkei, Japan)
David Yang (Raito, Inc.)

CHAPTER 1. INTRODUCTION

The Deep Mixing Method (DMM) is an in situ soil treatment technology whereby the soil is blended with cementitious and/or other materials. These materials are widely referred to as "binders" and can be introduced in dry or slurry form. They are injected through hollow, rotated mixing shafts tipped with some type of cutting tool. The shaft above the tool may be further equipped with discontinuous auger flights and/or mixing blades or paddles (Figures 1 and 2). These shafts are mounted vertically on a suitable carrier, usually crawler-mounted, and range in number from one to eight (typically two to four) per carrier, depending on the nature of the project, the particular variant of the method, and the contractor. Column diameters typically range from 0.6 to 1.5 m, and may extend to 40 m in depth. In some methods, the mixing action is enhanced by simultaneously injecting fluid grout at high pressure through nozzles in the mixing or cutting tools.

The cemented soil material that is produced generally has a higher strength, lower permeability, and lower compressibility than the native soil, although total unit weight may be less. The exact properties obtained reflect the characteristics of the native soil, the construction variables (principally the mixing method), the operational parameters, and the binder characteristics.

The original concept appears to have been developed more than 40 years ago in the United States, although contemporary deep mixing technology reflects mainly Japanese and Scandinavian efforts over the last three decades. The main applications in Japan involve ground treatment for transportation and harbor facilities in soft native or reclaimed soils, and examples of such applications have also grown in frequency in the United States, China, and Western Europe during the 1990s. In these highly urbanized and industrialized countries, the value of DMM to implement hazardous waste control and seismic retrofit solutions has also been widely exploited. Such market potential has encouraged certain U.S. contractors to attempt to develop their own proprietary systems, although the resources and ingenuity of the Japanese contractors have tended to preserve the perception of a technological superiority in their favor.

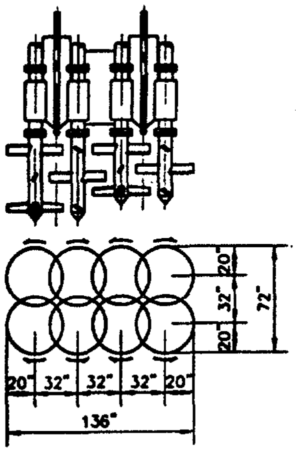
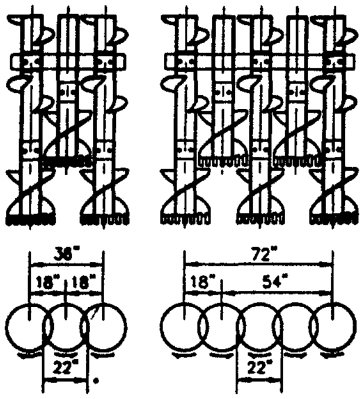
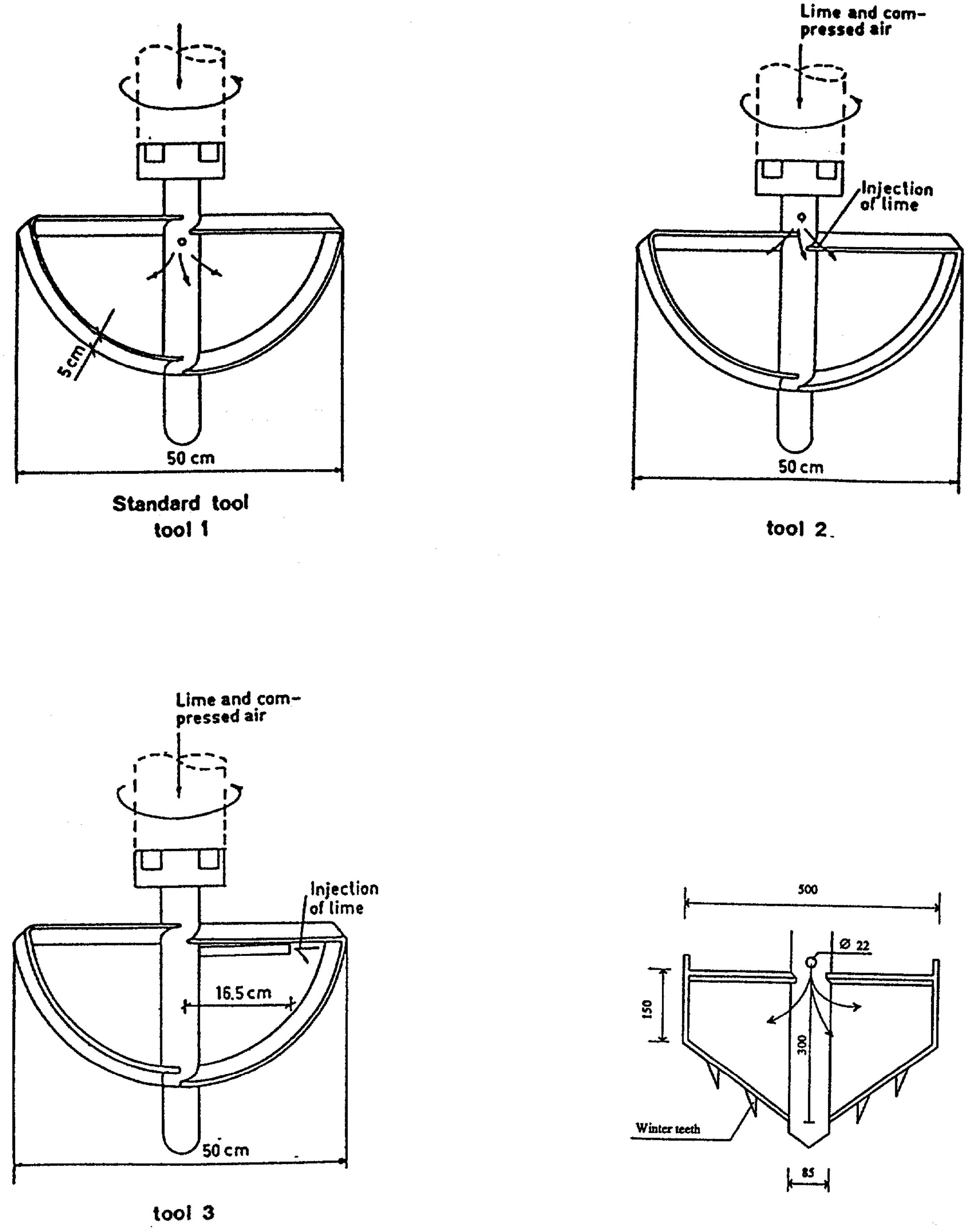
Title	**CDM** **(Cement Deep Mixing)**	**SMW** **(Soil Mix Wall)**
Sketches of Representative Mixing Mechanism	 φ = 39" to 63" available 1 ft = 0.305 m	 φ = 22" to 40" available 1 ft = 0.305 m
Descriptions	Rotation of multiple axis shafts create relative movement and shear in soil for soil-reagent mixing.	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.
Number of Mixing Shafts	2, 4, 6, or 8 shafts.	1, 2, 3, or 5 shafts.
Major Reagents	Cement or lime slurry.	Cement-bentonite slurry, bentonite slurry, clay slurry, or other stabilizing reagent slurries.
Applicable Surface Soils	Very soft silt and clay or very loose sandy soils (usually undersea).	Soft to hard silt and clay, loose to very dense sand, gravel, and cobble soils. Cobble and boulder soil and bedrock with predrilling.
Major Applications	Large-scale soil stabilization of sea floor for offshore or waterfront development.	Continuous walls for excavation support and groundwater control; Column blocks, lattice, or areal patterns for stabilization.
Remarks	Developed by Port and Harbor Research Institute.	Developed by Seiko Kogyo, Co., Ltd.

Figure 1. Two typical Japanese DMM systems showing the principles of end mixing (CDM) and shaft mixing (SMW) (Taki and Yang, 1990).



Standard tool
tool 1

tool 2.

tool 3

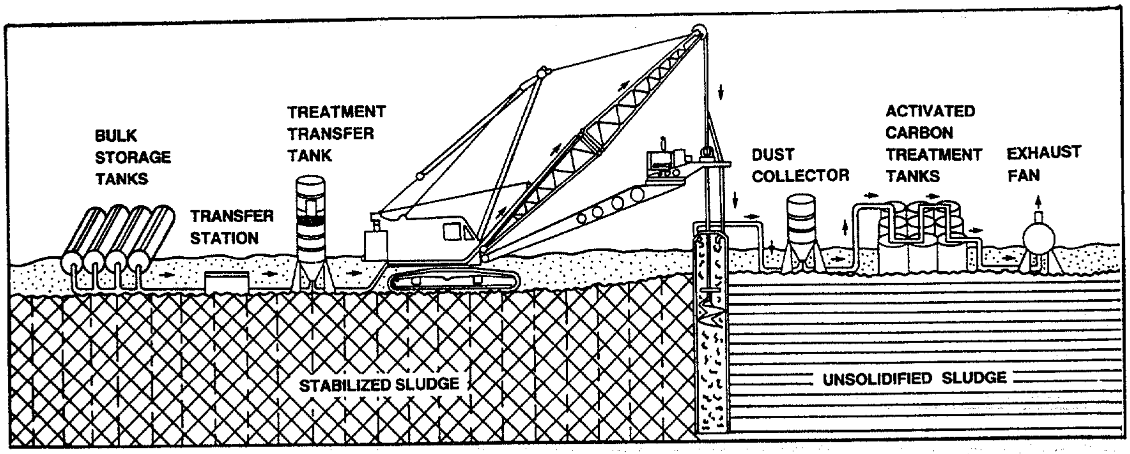
Figure 2. Typical end mixing tools used in the Swedish Lime Cement Column method (Stabilator Technical Information, 1992).

The smaller number of Scandinavian contractors also have extensive experience in treating very soft, compressible clays with lighter equipment producing lime or lime/cement columns for settlement control and embankment stabilization. They are also promoting their systems internationally, directing their attention to parts of the United States, as well as the Baltic countries. Focusing on infrastructure applications, the Scandinavians have found their methods to be cost-effective, fast, and technically and economically favorable compared to traditional methods (Holm, 1997).

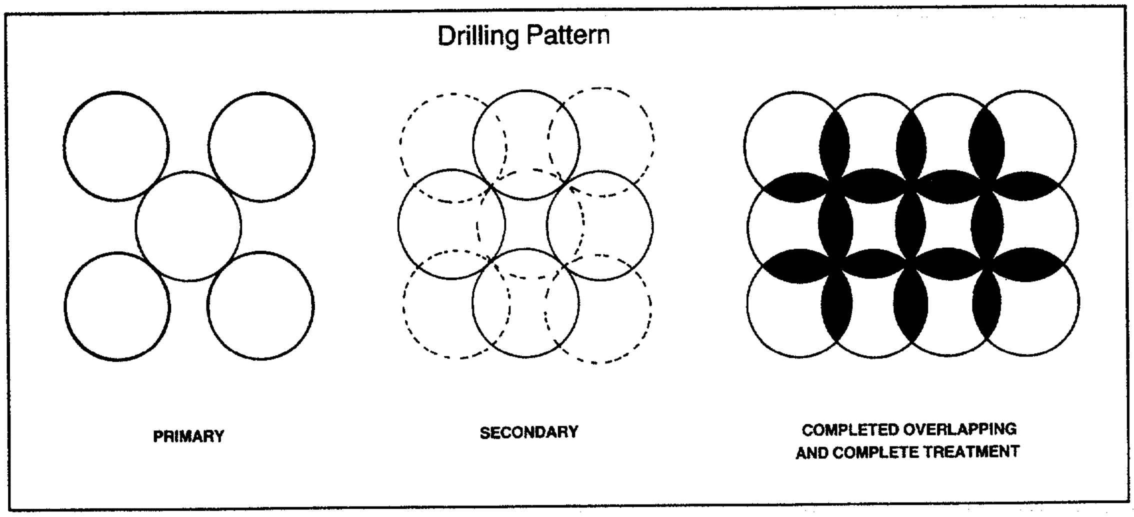
During the last decade, contractors involved primarily in hazardous waste fixation have developed techniques of in situ mixing using broadly similar methods and equipment to DMM. Using dry binders, a shaft rotated by a high-torque turntable, and special equipment to capture fugitive dust and vapors, these methods can provide individually treated soil columns up to 10 m deep, and up to 4 m in diameter (Figure 3). Such techniques are described within this report only as and where they may be used in certain geotechnical applications (e.g., in the construction of gravity retaining walls).

This report first traces the historical development of the various proprietary methods and provides a structured summary of applications. It also compares the applicability of DMM with other competitive forms of ground treatment and improvement. The bulk of the report, however, constitutes a description of each of the individual methods, focusing on the equipment, the procedures, and the properties of the treated soil. Out of this review has evolved a rigorous classification covering the different methods so that the reader can better appreciate their intricate interrelationships. The report continues by describing the nature of the market in North America, Japan, and Scandinavia, while observations are also made on the various potential barriers to further growth in the United States. This report incorporates some factual data from an earlier Federal Highway Administration (FHWA) draft report (1996), but follows a different structure and philosophy.

It should be recognized that the papers cited in this report may only represent a small proportion of the total knowledge published internationally. For example, Terashi (1997a) records that



Crane mounted mixing system advancing through sludge layer.



Primary and secondary overlapping bore patterns.

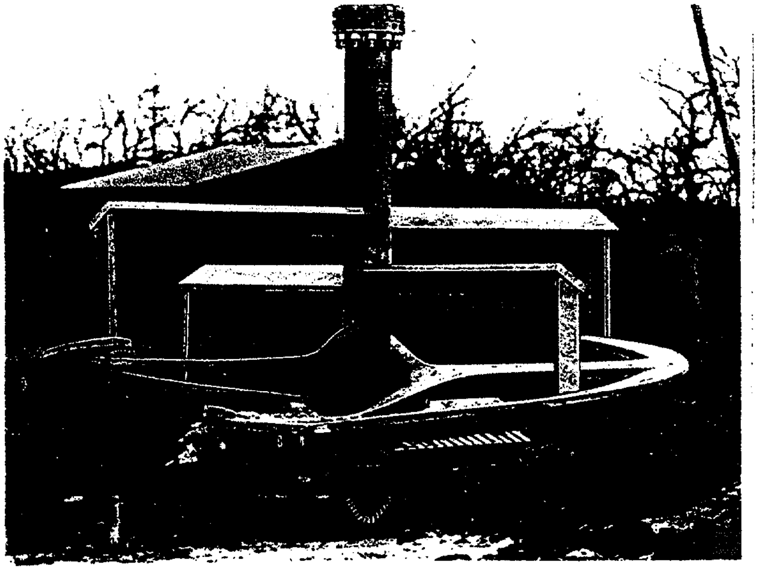


Figure 3. Shallow Soil Mixing (SSM) method principles and equipment (Geo-Con, Inc., 1990).

“more than two hundred interesting achievements have been reported in the Japanese language in the annual conventions both of [the] Japanese Geotechnical Society and [the] Japan Society of Civil Engineers,” while there is an equally rich and informative literature in the Swedish and Finnish languages.

These factors notwithstanding, the authors believe that the observations and classifications offered in this report are applicable beyond the scope of its particular body of research data, noting also that comments in peer reviews by several foreign specialists have been incorporated. In addition, data from the lectures presented at the Deep Mixing Short Course, held at the University of Wisconsin-Milwaukee on August 27 and 28, 1998, have also been fully absorbed.

As a final introductory note, readers will observe the frequent use of acronyms throughout the text. These are explained in full upon their first appearance only. A full listing of these acronyms as they apply to the various Deep Mixing Method systems is provided within Chapter 5.

CHAPTER 2. HISTORICAL DEVELOPMENT

The following listing summarizes the dates of key events in the development of DMM technology, and contains references to some of the many variants of DMM, which are detailed in later chapters. The chronology is introduced at this early point in the report so that the classification and evolution of the different DMMs can be more clearly appreciated in the subsequent chapters. Complementary information on research projects has recently been provided by Porbaha (1998).

1954	Intrusion Prepakt Co. (United States) develops the Mixed in Place (MIP) Piling Technique (single auger), which sees only sporadic use in the United States.
1961	MIP already used under license for more than 300,000 lineal meters of piles in Japan for excavation support and groundwater control. Continued until early 1970s by the Seiko Kogyo Company, to be succeeded by diaphragm walls and DMM (SMW) technologies.
1967	The Port and Harbor Research Institute (PHRI, Ministry of Transportation, Japan) begins laboratory tests, using granular or powdered lime for treating soft marine soils (DLM). Research continues by Okumura, Terashi et al. through early 1970s to: (1) investigate lime-marine clay reaction, and (2) develop appropriate mixing equipment. Unconfined compressive strength (UCS) of 0.1 to 1 MPa achieved. Early equipment (Mark I-IV) used on first marine trial near Hameda Airport (10 m below water surface).
1967	Laboratory and field research begins 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), Euroc AB, and BPA Byggproduktion AB). This follows observations by Paus on fluid lime column installations in the United States.
Late 1960s	China reported to be considering implementing DLM concepts from Japan.
1972	Seiko Kogyo Co. of Osaka, Japan begins development of Soil Mixed Wall (SMW) method for soil retaining walls, using overlapping multiple augers (to improve lateral treatment continuity and homogeneity/quality of treated soil).
1974	PHRI reports that the Deep Lime Mixing (DLM) method has commenced full-scale application in Japan. First applications in reclaimed soft clay at Chiba (June) with a Mark IV machine developed by Fudo Construction Co., Ltd.

	Applications elsewhere in Southeast Asia follow the same year. (Continues to be popular until 1978 – 21 jobs, including two marine applications – when CDM and Dry Jet Mixing (DJM) overtake.)
1974	Intensive trials conducted with Lime Columns at Skå Edeby Airport, Sweden: basic tests and assessment of drainage action (columns 15 m long and 0.5 m in diameter).
1974	First detailed description of Lime Column method by Arrason et al. (Linden Alimaik AB).
1974	First similar trial embankment using Swedish Lime Column method in soft clay in Finland (6 m high, 8 m long; using 500-mm-diameter lime cement columns, in soft clay).
1975	Swedish paper on lime columns (Broms and Boman), and Japanese paper on DLM (Okumura and Terashi) presented at same conference in Bangalore, India. Both countries had proceeded independently to this point. Limited technical exchanges occur thereafter.
1975	Following their research from 1973 to 1974, PHRI develops the forerunner of the Cement Deep Mixing (CDM) method using fluid cement grout and employing it for the first time in large-scale projects in soft marine soils offshore. (Originally similar methods include DCM, CMC (still in use from 1974), closely followed by DCCM, DECOM, DEMIC, etc., over the next five years).
1975	First commercial use of Lime Column method in Sweden for support of excavation, embankment stabilization, and shallow foundations near Stockholm (by Linden Alimak AB, as contractor and SGI as consultant/researcher).
1976	Public Works Research Institute (PWRI) Ministry of Construction, Japan, in conjunction with Japanese Construction Machine Research Institute begins research on the DJM method using dry powdered cement (or less commonly, quick-lime); first practical stage completed in late 1980. Representatives of PHRI also participate.
1976	SMW (Soil Mixed Wall) method used commercially for first time in Japan by Seiko Kogyo Co.
1977	CDM (Cement Deep Mixing) Association established in Japan to coordinate technological development via a collaboration of industrial and research institutes. (Now has about 50 members.)

1977	First design handbook on lime columns (Broms and Boman) published by Swedish Geotechnical Institute (describes unslaked lime applications only).
1977	First practical use of CDM in Japan (marine and land uses).
1977	China commences research into CDM, with first field application in Shanghai using its own land-based equipment in 1978.
1979	Tenox Company develops Soil Cement Column (Teno Column) system in Japan: subsequently introduced into the United States in 1992.
1980	First commercial use in Japan of DJM, which quickly supersedes DLM thereafter (land-use only).
1981	Prof. Jim Mitchell presents general report at ICSMFE (Stockholm) on lime and lime cement columns for treating plastic, cohesive soils, increasing international awareness.
Early 1980s	DJM Association established in Japan. (Now with more than 20 members.)
1983	Eggestad publishes state-of-the-art report in Helsinki dealing with new stabilizing agents for Lime Column method.
1984	SWING method developed in Japan, followed by various related jet-assisted (W-R-J) methods in 1986, 1988, and 1991.
1985	First commercial use of Lime Cement Column method in Finland.
1985	SGI (Sweden) publishes 10-year progress review (Åhnberg and Holm).
Mid 1980s	First application of lime cement columns in Norway (under Swedish guidance).
1986	SMW Seiko Inc. commences operations in the United States under license from Japanese parent Seiko Kogyo Co. and thus introduces contemporary DMM to U.S. market.
1987	The Bachy Company in France develops "Colmix" in which mixing and compacting the cemented soil is achieved by reverse rotation of the multiple augers during withdrawal. Developed as a result of research sponsored by French national highways and railroads. Appears to be first European development outside Scandinavia.
1987 – 1989	SMW method used in massive, landmark ground treatment program for seismic retrofit at Jackson Lake Dam, WY.

1987	Cementation Ltd. reports on use of their single auger deep mixing system in U.K. (developed in early-mid 1980s).
1987	First experimental use of CDM for ground treatment (involving the Takenaka Company) in China (Xingong Port, Taijin).
1987	First use of DMM for excavation support in Shanghai, China.
1987 – 1988	Development by Geo-Con, Inc. (United States) of DSM (Deep Soil Mixing – 1987) and SSM (Shallow Soil Mixing – 1988) techniques.
1989	The Trevisani and Rodio Companies in Italy develop their own DMM version, starting with dry mix injection, but also developing a wet mix method.
1989	Geo-Con uses SSM technique for gravity wall at Columbus, GA.
1989	DMM technology included in Superfund Innovative Technology Evaluation Program of the U.S. Environmental Protection Agency for demonstration as a technology for in situ solidification/stabilization of contaminated soils or sludges. Subsequently used in practice.
1989	Start of exponential growth in use of lime cement columns in Sweden.
1989	The Tenox Company reports more than 1000 projects completed with SCC method in Japan, prior to major growth thereafter (9000 projects to end of 1997, with a $100 to 200 million/year revenue in Japan and elsewhere in Southeast Asia).
1990	New mixing equipment developed in Finland using cement and lime (supplied and mixed separately): capable of creating columns greater than 20 m deep, 800 mm in diameter, through denser, surficial layers.
1990	Dr. Terashi, involved in development of DLM, CDM, and DJM since 1970 at Port and Harbor Research Institute, Japan, gives November lectures in Finland. Introduces more than 30 binders commercially available in Japan, some of which contain slag and gypsum as well as cement. Possibly leads to development of "secret reagents" in Nordic Countries thereafter.
1991	Low Displacement Jet Column Method (LDis) developed in Japan.
1991	Bulgarian Academy of Sciences reports results of local soil-cement research.
1991	Geotechnical Department of City of Helsinki, Finland, and contractor YIT introduce block stabilization of very soft clays to depths of 5 m using a variety of different binders.

Early 1990s	First marine application of CDM at Tiajin Port, China: designed by Japanese consultants (OCDI) and constructed by Japanese contractor with his own equipment (Takenaka Doboku).
1992 – 1994	SMW method used for massive earth retention and ground treatment project at Logan Airport, Boston, MA.
1992	Chinese Government (First Navigational Engineering Bureau of Ministry of Communications) builds first offshore CDM equipment "fleet", using Japanese technology used for first time (1993) at Yantai Port. (Reportedly the first wholly Chinese Design-Build DMM project.)
1992	Jet and Churning System Management (JACSMAN) developed by Fudo Company and Chemical Grout Company in Japan.
1992	New design guide (STO-91) produced in Finland based on experience in 1980s and research by Kujala and Lahtinen (involving 3000 samples from 29 sites).
1992 – 1993	First SCC installation in United States (Richmond, CA).
1993	First DMM activities of Millgard Corporation (United States), largely for environmental work.
1993	DJM Association Research Institute publishes updated Design and Construction Manuals (in Japanese).
1993	CDM Association claims 23.6 million m^3 of soil treated since 1977.
1994	SMW claims 4000 projects completed worldwide since 1976, comprising 12.5 million m^2 (7 million m^3).
1994	SMW used for 19,000 m^2 of soil retention on Los Angeles Metro (Hollywood Boulevard), CA.
1994	CDM Association manual revised and reissued (in Japanese).
1994	First commercial application of original Geojet system in the United States (Texas) following several years of development by Brown and Root Company.
1994	DJM Association claims 1820 projects completed up to year's end (total volume of 12.6 million m^3).
Mid 1990s	First use of lime cement columns in Poland (Stabilator Company).

1995	Finnish researchers Kukko and Ruohomäki report on intense laboratory research program to analyze factors affecting hardening reactions in stabilized clays. Discusses use of new binders (e.g., slag, pulverized flyash, etc.).
1995	Swedish government sets up new Swedish Deep Stabilization Research Center at SGI (1995 to 2000: $8 to 10 million budget): Svensk Djupstabilisering. Consortium includes owners, government, contractors, universities, consultants, and research organizations co-coordinated by Holm of SGI and Broms as "scientific leader." Research planned: creating an experience database; properties of stabilized soil; modeling of treated soil structures; quality assurance; and work performance. Results to be published in a series of reports.
1995	Finnish government sets up similar new research consortium until 2001 for the ongoing Road Structures Research Programme (TPPT) to improve overall performance of road structures (similar to Swedish program members and scope).
1995	From 1977 to 1995, more than 26 million m^3 of CDM treatment reported in Japan.
1995	Swedish Geotechnical Society publishes new design guide for lime and lime cement columns (P. Carlsten) focusing on soft and semi-hard columns. English version released in 1996.
1995	From 1980 to 1996, about 15 million m^3 of DJM treatment reported in Japan.
1995 – 1996	SMW method used for massive soil retention scheme at Cypress Freeway, Oakland, CA.
1996	Report on use in Japan of FGC-DM (Flyash-Gypsum-Cement) method (a form of CDM).
1996	SGI (Sweden) publishes 21-year experience review.
1996	First commercial use of lime cement columns in the United States (Stabilator Company in Queens, NY).
1996	More than 5 million lineal meters of lime and lime cement columns reportedly installed in Sweden since 1975. Annual production in Sweden and Finland now averages about the same output. Sweden's market is 2 to 4 times larger than Finland's, which in turn far exceeds Norway's.
1996 – 1997	Hayward Baker, Inc. installs 1.2- to 1.8-m diameter DMM columns for foundations, earth retention, and ground improvement in various U.S. sites.

1997 – to date	SMW method used for massive ground 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 the United States of modified Geojet system (Condon Johnson and Associates at San Francisco Airport, CA).
1997	Major lime cement column application for settlement reduction at I-15, Salt Lake City, UT (proposed by Stabilator USA, Inc.).
1997	Geo-Con, Inc. uses DMM (with concrete facing) for permanent excavation support, Milwaukee, WI.
1997 – 1998	Master Builders Technologies develop families of dispersants for soil (and grout) to aid DMM penetration and mixing efficiency.
1998	First application by Trevi-ICOS Corporation of their DMM in Boston, MA.
1998	Raito, Inc. establishes office in California, offering various DMM technologies under license from Japan (including DJM, CDM, and Raito Soil Mixed Wall), and wins first project in California in early 1999.
1998	Geo-Con, Inc. conduct full-scale demonstration of VERTwall DMM concept in Texas.
1998	First Deep Mixing Short Course presented in the United States (University of Wisconsin – Milwaukee, August).
1998	Formation of Deep Mixing Subcommittee of Deep Foundations Institute during annual meeting in Seattle, WA, October.

CHAPTER 3. APPLICATIONS

The various DMM techniques can be used to produce a wide range of treated soil structures as shown in Figure 4 (Yang, 1997):

- Single elements.
- Rows of overlapping elements (walls or panels).
- Grids or lattices.
- Blocks.

The particular geometry chosen is, of course, dictated by the purpose of the DMM application, and reflects the mechanical capabilities and characteristics of the particular method used.

In overview, Table 1 summarizes the applicability of DMM as related to soil type and desired effect, in comparison with other technologies. The main groups of applications are as follows, with the countries in parentheses indicating their major global application:

1. Hydraulic cut-off walls (Japan, U.S.).
2. Excavation support walls (Japan, China, U.S.).
3. Ground treatment (Japan, China, U.S.).
4. Liquefaction mitigation (Japan, U.S.).
5. In situ reinforcement, piles, and gravity walls (Sweden, Finland, France).
6. Environmental remediation (U.S., U.K.).

Further data on global usage are provided in chapter 6. Figures for chapter 3 are provided at the end of chapter text, for ease of reference.

3.1 Hydraulic Cut-Off Walls

Hydraulic cut-offs are created by installing overlapping columns or panels consisting of several connected adjacent columns to intercept the seepage flow path (Figure 5). The columns/panels are installed typically through the permeable strata to some cut-off level, usually the top of the bedrock. The soils treated are generally highly permeable coarse deposits, or interbedded strata of fine- and coarse-grained soils.

A major seepage control project was conducted in conjunction with the installation of a new radial gated spillway structure for Lake Cushman Dam, near Hoodsport, WA (Yang and Takeshima, 1994). Two embankments were constructed adjacent to the headworks structure of the spillway, which was founded on low-permeability bedrock. DMM walls were installed through the cores of these embankments (Figure 6) to bedrock to control seepage through the embankment fill and the underlying permeable glacial deposits. The maximum depth of the treatment was 43 m, and the cut-offs were 51 to 61 m long.

Walker (1994) reported on the use of DMM at Lockington Dam, OH – the "first U.S. application to raise the core of an existing dam." More than 6200 m^2 of cutoff wall, 6.5 m deep, was installed from the crest of an existing dam to treat permeable materials overlying the hydraulically placed clay core.

An innovative application in Japan is to install a DMM cut-off wall in porous strata or limestone terrain to create a subsurface dam (Figures 7a and 7b). Such dams are used to create subsurface reservoirs for irrigation purposes. Near coastal regions, subsurface dams are also used for the prevention of saltwater intrusion into freshwater supplies (Nagata et al., 1994). About 10 subsurface dams have so far been constructed in Japan to a maximum depth of 65 m.

DMM walls have also been used for pollution containment, to remediate defects in existing soil bentonite cut-offs (Yang, 1997), and in portions of the Sacramento levee system (Figure 7c).

Either soil/cement walls (UCS of 0.1 to 2 MPa and a permeability of 10^{-8} to 10^{-9} m/s,) soil-bentonite, or soil-clay-bentonite walls (permeability of 10^{-9} to 10^{-10} m/s) can be formed (the latter as low-strength cut-offs at sites with low differential heads).

3.2 Excavation Support Walls

Such structures are similar to cut-off walls except that the treated soil material is typically engineered to be more durable and/or of higher strength, and steel elements are placed before the treated soil stiffens (Figure 8). This creates a structural wall for both excavation support and groundwater control, and this application was the driving force behind the development of the SMW method (Taki, 1997). Major recent projects in the United States include structures for the Ted Williams Tunnel approach, Boston, MA; the Cypress Freeway Replacement Project, Oakland, CA; the Islais Creek Sewerage Project, San Francisco, CA; the Marin Tower, Honolulu, HI (Yang and Takeshima, 1994); and the Lake Parkway, Milwaukee, WI (Figure 9). The Milwaukee project featured DMM as part of the final, permanent anchored wall (Figure 10). As of 1998, more than 20 excavation support walls had been built in the United States (Nicholson and Jasperse, 1998), three of those involving a fully-treated "gravity wall" concept (without anchors or braces) and one of these being permanent.

In Singapore, a 225-m long by 23-m wide excavation was made for the construction of Bugis Station for the Mass Rapid Transit system in an urban area (Chew et al., 1993). The excavation was 18 m deep, and flanked by existing structures underlain by soft, marine clays to a depth of 41.5 m. Tangent DMM columns, 1.0 to 1.2 m in diameter, were installed around the perimeter of the excavation, and the resulting wall was braced with seven stage struts.

Shao et al. (1998) described how DMM techniques have been used since 1987 to create retaining structures in Shanghai. These have generally been conceived as gravity structures of the type shown in Figure 11. They describe the example of the Sunlight Park Hotel, which involved an excavation in soft fills and clays of 94 x 63 x 6.75 m, adjacent to existing structures. On two sides, the overall width of the wall was 3.2 m (four rows of DMM columns) and on the other two, the width was 4.7 m (five rows). The walls were constructed a minimum of 10 m deep, and the middle row was 3 m deeper to act also as an hydraulic cut-off. The authors report that internal reinforcement with bamboo is being considered since its E-value is closer to that of the treated soil than steel, and considerably cheaper.

Yet another concept was described by Elliott (1989): a circular DMM structure comprising three concentric unreinforced overlapping rings of 750-mm-diameter columns was constructed to permit shaft construction in England (Figure 12). Long-term resistance to groundwater uplift pressures was proposed by fixing the final, precast element, shaft lining to the cemented soil with soil nails. A similar application was later used by the same company to form five manholes, each 4 m inside diameter, through glacial silty sand and laminated clay in northern England, to a maximum depth of 15 m (Figure 13). The individual column diameter was again 750 mm. The technique was chosen in this particular area due to: (1) the close proximity of adjacent structures; (2) the close proximity of vibration-sensitive devices and services; and (3) the variable ground conditions and high water table. These are common factors in selecting DMM in such applications.

3.3 Ground Treatment

Pretreatment by DMM increases the strength and reduces the compressibility of natural and placed soils, and thus can provide ground stability and control of ground movements during surface and underground construction. Indeed, large-scale civil works in marine environments, such as the construction of manmade islands, tunnels, harbors, seawalls and breakwaters (Figure 14) fostered the development of the DMM technology, culminating in its extensive usage in the construction of the Trans-Tokyo Bay Tunnel (Figures 15 and 16). More than 1.8 m^3 of ground treatment was conducted (Uchida et al., 1996; Unami et al., 1996). DMM was used extensively in Boston, MA to create in situ buttresses (Nicholson and Chu, 1994) for excavation stabilization (Figure 17) and was specified on the Fort Point Channel project to stabilize existing soils to facilitate tunneling.

The buttress concept had previously been used as a planned, engineered solution to help stabilize a deep foundation excavation in soft clays in Taipei, Taiwan (Liao et al., 1992). DMM columns were installed within the base of an 11.9-m-deep braced excavation, adjacent to existing seven-story buildings. The columns (0.8 m in diameter) were installed at a spacing of 2 m to a total depth of 11 to 17 m. Figures 18 and 19 illustrate the layout of the columns in this innovative and successful case history.

Yang et al. (1998) also described a case history providing a DMM solution as treatment/ improvement for the Tomei Freeway connecting Tokyo and Nagoya. A total of more than 50,000 m^3 of organic clays, peats, and fills were treated for use as the foundation of a new road embankment, box culvert and retaining walls (Figure 20). Various cement contents and pile spacings were selected in response to the type of soil and the structural requirements. For example, the area treatment ratios were 35%, 50%, and 78.5%, respectively, for the three applications noted above. The work was completed by two rigs in 7 months without disrupting the operation of the existing four-lane freeway.

Figure 21 shows a cross section of a deep mixed wall installed to support the foundation of a quay wall at a waste disposal site in Japan (Kawasaki et al., 1981). The wall was installed to a depth of 40 m below the seabed level over a length of 65 m. Within the immediate vicinity of the quay wall, 1.5-m columns, 9 m deep, were installed to reinforce the treated ground against shear failure and to reduce stress concentrations at the top of the wall. The undrained shear strength of the treated material was 300 kPa.

Figure 22 shows stabilization of a river bank slope in Kumamoto-ken, Kyushu Island, Japan (CDM Association, 1994). Reportedly, 5628 m^3 of DMM columns were installed in this application. A DMM wall, 79 m long, 20 to 27 m wide, and 13 m below the seabed, was also installed to stabilize the foundation of a breakwater in Hiroshima, Japan (Figure 23).

Figure 24 shows the column layout and cross section of the stabilization of a waterfront birthing and unloading facility in Pascagoula, MS. A total of 8800 m^2 of platform was stabilized to a depth of 15 m. The average 28-day UCS from cured wet samples was 1.2 MPa.

3.4 Liquefaction Mitigation

The uses of DMM for liquefaction mitigation include liquefaction prevention, reinforcement of liquefiable soil, and pore pressure reduction.

Liquefaction prevention by DMM is used where other more conventional remedial measures are not viable for depth or economic reasons. A perimeter wall is first installed to isolate and contain cohesionless soils under the existing structure. The groundwater within the perimeter wall is then permanently lowered to provide a dry or non-liquefiable zone under the structure.

Reinforcement of liquefiable soils can be provided by block, wall, or lattice DMM patterns. The use of a grid or lattice pattern is especially effective due to its ability to engage the entire treated area as a unit, and thus fully mobilize the compressive strength of the cemented soil volume. The use of single columns or column groups cause stress concentrations and the development of bending stresses leading to failure. Conceptually, and according to Mitchell (1997) referring to the work at Jackson Lake Dam (Figure 25) the mechanism of improvement was threefold:

(1) The "cells" absorb shear stresses and reduce the amplitude of the lateral granular movement and the development of excess pore pressure.
(2) The confinement prevents lateral spreading.
(3) The compressive strength of the columns minimizes settlement.

Numerous research studies have been performed to determine the effectiveness of using lattice-type DMM structures to reduce excessive porewater build-up in loose sands during seismic events. The methods of approach include three-dimensional finite element simulation and small-scale to large-scale dynamic model tests on shaking tables and in centrifuges. These studies indicate that lattice-type DMM structures effectively reduce the excess porewater pressure. Using these concepts, numerous structures have been designed and constructed on very loose sand. As examples, Figures 26 and 27 (Matsuo et al., 1996) illustrate the use of such structures under dikes.

Severe damage was induced in the Kobe area of Japan during the magnitude 7.2 earthquake in 1995. The performance of the Hotel and Terminal Building on the pier at Kobe Harbor was closely investigated. The results indicate that there was no structural damage to the hotel, which occupied the major portion of the pier and was under construction on reclaimed sand. In contrast, the sea walls surrounding three sides of the hotel suffered large lateral movements toward the sea, as did other sea walls in the area. The hotel was supported by drilled piers; however, to prevent ground liquefaction and the accompanying lateral flow, 15.8-m-deep DMM grids had been installed (Figure 28). Based on the detailed studies, it appears that no liquefaction or lateral flow occurred in the foundation soils enclosed by the grids, and so it may be concluded that such grids are very effective in preventing ground liquefaction and the resultant lateral soil flow during major earthquakes. In this regard, it may be noted that Taki and Bell (1997) claim that low-rise buildings supported on individual "Tenocolumns" (i.e., SCC method) also performed well during the Kobe event.

The reconstruction of the Torishima Dike following the Kobe earthquake is another excellent example of the application of the technique (Yang et al., 1998). The dike is 7 m high, and due to the liquefaction of 10 to 14 m of foundation soil, more than 2 km of the dike failed. Immediate repair was necessary before the arrival of the annual hurricane season in September. Post-failure studies showed 10 m of interbedded layers of sand and silt with Standard Penetration Test (SPT) values of 3 to 10. DJM was selected for many reasons and a grid pattern of treatment was designed (Figure 29) to:

1. Reduce shear strain and build-up of excess pore pressure.
2. Contain local liquefied zones if liquefaction occurred.
3. Reinforce the foundation and increase factors of safety against slope failure or lateral spreading.

At peak construction, 32 rigs were mobilized (half of Japan's capacity) to provide 28-day target strengths of 0.5 MPa. These strengths were exceeded in the sand. Furthermore, the DJM product was regarded as "semi-permeable" and thus reduced the impact on the groundwater table and the natural groundwater flow. More than 600,000 m^3 of liquefiable soils were treated within 3 months.

Babasaki and Suzuki (1996) describe another particularly illustrative case history where DMM was used in four distinct ways to mitigate against liquefaction on a Tokyo waterfront site featuring reclaimed ground over soft clays (Figure 30):

- Low-strength block treatment to permit drilled pile installation.
- Lattice treatment to "surround" the piles.
- Slope stabilization and the provision of a competent operating surface for heavy equipment.
- Ground treatment to provide support for utility conduits and earth retaining walls.

In the United States, the most significant liquefaction mitigation project involving DMM was conducted at Jackson Lake Dam, WY, between 1987 and 1989 (Figure 25), where more than 130,000 linear meters of columns were installed forming grids to a maximum depth of 33 m (Taki and Yang, 1991).

More recently, DMM columns were installed at the site of California State University's new Marine Laboratory to treat the ground beneath a foundation wall (Francis and Gorski, 1998). The original laboratory facility was destroyed by liquefaction during the 1989 Loma Prieta Earthquake. The new facility is being constructed south of the original site, on dune deposits comprising very loose to dense, clean, medium to fine sands. A single row of 113 columns was installed to a depth of between 4.5 and 6 m. The 1-m-diameter columns were spaced 1.2 to 2.4 m apart. Unconfined compressive strengths of 1.4 MPa at 28 days were required, and actual strengths varied from 1.7 to 13.8 MPa. The site is in close proximity to a known, sacred Native American burial ground containing archeologically significant artifacts. One of the advantages of DMM that contributed to its approval for the project was that artifacts would not be removed during ground treatment.

In the same region, Stabilator USA, Inc. has installed lime cement columns in oblong cells for seismic retrofit in San Francisco Bay Area Rapid Transit (BART) System. These cells treated 37% of the total soil volume.

3.5 In Situ Reinforcement (or Ground Improvement) and Piles

DMM structures, usually in the form of relatively closely spaced single columns (Figure 31), walls, or lattices (for high lateral loads) have been widely used in Scandinavia, and also in Japan and France as in situ reinforcement. The major applications have been to reduce settlements under embankments, to improve slope stability, and to support light buildings and bridges. Typical examples are cited by Noriyasu et al. (1996, Figure 32), who constructed a "floating foundation," and Dong et al. (1996, Figure 33), who exploited the in situ reinforcement concept for slope stabilization.

Although no commercial large-scale DMM applications have yet been recorded in the United States, there are many examples of the use of smaller diameter columns for similar applications, especially in the South; this application is also likely to be exploited in the soft clays under the reconstructed I-15 in Salt Lake City, Utah, where more than 1 m of settlement is predicted in the clay foundation soils unless treatment/improvement is conducted. Figure 34 illustrates the concept, showing also the potential improvement that can be derived from the drainage function. Such columns can also accelerate settlement and are often used in combination with preloading. In addition, it would also seem that such columns will be used to stabilize the organic and clayey soils underlying the path of the new high-speed railway line to be built in western Holland over the next 3 years.

Not dissimilarly, discrete elements can be introduced to act as load-bearing columns, or piles. These may range from the low-capacity lime cement columns to the 360-t capacity, heavily reinforced caisson that can be produced by the GeoJet system (Reavis and Freyaldenhoven, 1994). However, the Scandinavian concept of in situ reinforcement (soil/structure interaction) does not require the individual column to have a high-strength (say, 0.15 MPa) maximum. This soil/structure interaction concept, often combined with preloading, has proved to be efficient and cost-effective compared to other methods. The use of lime in the introduced material also governs a long-term strength increase, which is valuable in some applications.

Lime cement columns were installed to support a 42-m-diameter, 20-m high fuel tank at an oil refinery in Singapore (Ho, 1996). The columns (0.4 m in diameter) were installed to a depth of 13 m in the arrangement shown in Figure 35. The piles were installed through 2.7 to 6.6 m of fill material over 4.8 to 9 m of peaty soft clay. The water table was 0.3 m below ground surface. The columns were installed to reduce differential settlement and increase the bearing capacity of the foundation soils.

DMM has been used to support bridge abutments and reduce earth pressure and settlement behind the abutments. DJM methods were used to install 2674 columns, 1 m in diameter and 8.4 to 9.2 m deep, to protect the piers of a bridge in Japan (Figure 36). The UCS of the treated materials ranged from 200 to 400 kPa (25% of the laboratory strength value), and cement contents ranged from 120 to 450 kg/m^3, with an average of 150 kg/m^3 (DJM Association, 1993).

Lime cement columns were installed to stabilize a railway embankment in Bulgaria (Evstatiev et al., 1995) against excessive settlement (Figure 37). Columns 0.25 m in diameter, 8 to 9 m long, at a spacing of 2.5 m, were installed in three parallel rows. The undrained shear strength of the treated soil was 0.235 MPa.

DMM was also used to stabilize the toe of an embankment constructed to retain coal waste in Japan (Xu, 1996). The embankment was constructed on a soft mud deposit 4 to 9 m thick, and failure of the base of the embankment occurred during construction. The soil at the base of the embankment was treated to a depth below the mud layer to increase shear strength along the slide plane (Figure 38).

In late 1997, Geo-Con, Inc. announced the development of a new concept utilizing the principles of in situ reinforcement into a vertical earth retention application ("VERT" system). As shown in Figure 39, DMM is used to create a composite gravity wall system, which is both watertight and self-supporting (i.e., no internal braces or ground anchors are needed). A bottom plug can also be installed with DMM, and all the work is completed before any excavation begins. The final wall facings are architectural only, since both temporary and permanent loads are resisted by the in situ reinforcement. This concept has a patent pending and has been extensively field tested (Nicholson and Jasperse, 1998).

3.6 Environmental Remediation

In situ solidification and stabilization to remediate contaminated soils and sludges have seen increasing acceptance and expanded use since the early 1990s. As a consequence of intensive laboratory studies, mixes with various reagents can be designed to reduce the leachability of soils and sludges containing metals, semi-volatile organic compounds, and low-level radioactive materials. By selecting appropriate equipment and procedures, the reagents can be uniformly injected at depths, and efficiently and reliably mixed with the soils or sludge present.

A two-phase, full-scale in situ solidification/stabilization program was implemented at a site in the San Francisco Bay area of California between 1992 and 1994. This site had been used for the manufacture of arsenical pesticides from the 1920s to the 1960s. The soils consisted of fine-grained alluvial deposits and Bay muds. Two reagents were used to treat the contaminated soil to a maximum depth of 8 m. Triple-auger mixing equipment was used to distribute the reagents sequentially and uniformly into soils at all depths. A total volume of 10,800 m^3 of contaminated soils with arsenic contents ranging from 500 to 5000 mg/kg were treated. More than 300 arsenic leachability tests were performed; none exceeded the Federal Toxicity Criterion for arsenic of 5 mg/L, according to Yang et al. (1995).

DMM was used to immobilize polychlorinated biphenyls (PCBs) in leaked transformer oil at a General Electric service shop in Haileah, FL. This work was performed as part of a U.S. Environmental Protection Agency site program (U.S. EPA, 1991). Two 3-m x 6-m areas were treated using an arrangement of overlapping columns (Jasperse and Ryan, 1992).

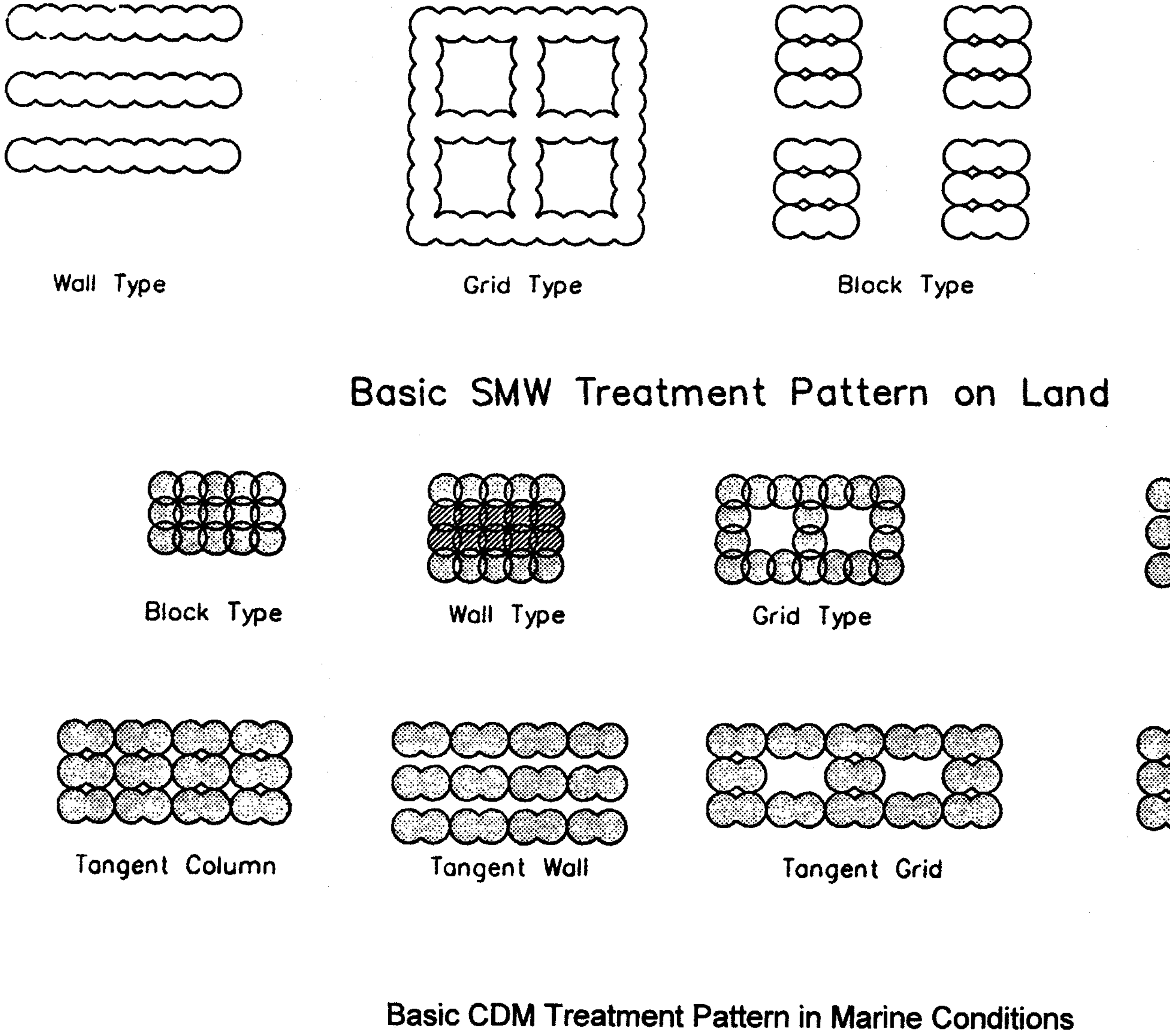
Walker (1992) described the stabilization of a block of soils contaminated with hydrocarbons extending 53 m along a highway in Pittsburgh, PA, prior to subsequent excavation and removal.

As shown in Figure 40, three rows of 2.4-m-diameter columns were installed on a 1.8-m x 2.0-m grid, although a low-headroom jet grouting machine had to be used for a limited number of columns under a bridge, and adjacent to a row of timber piles. This is a particularly illustrative use of a DMM technique selected primarily on the basis of its environmental suitability to solve a largely geotechnical problem.

DJM equipment was used as a type of vapor extraction system to recover volatile organic compounds (VOCs) at a contaminated clay site. The location of this site was not reported. Quicklime was applied into a flow of compressed air, injected at the end of the shaft, and mixed with the soil. The in situ water and the VOCs were vaporized by the heat of hydration, and the vapors were recovered through a hood at the ground surface (Figure 41). The vapors were treated in solvent recovery equipment, and the treated air was released to the atmosphere.

3.7 Other Classifications

Other attempts to classify the range of conventional DMM applications are shown in Figures 42, 43, 44, and 45. As noted by Terashi (1997b), new applications continue to be developed. For example, when a treated soil strength of as low as 0.1 MPa is required, the cement content must be minimized. However, when wet binder methods are used, a reduction in the volume of grout to be injected will lead to difficult penetration and very inefficient mixing. The development is to use sufficiently large volumes of stable, low-strength grout (using low cement, but high flyash contents, as in the FGC-CDM method, Chapter 5). On projects in urban sites founded on thick deposits of soft soils, it may be very costly to drive sheet piling to an appropriately competent horizon. However, a pretreatment by DMM, providing an engineered, low-strength, and artificial bearing stratum can be an excellent solution. The Electric Power Development Company (EPDC) in Japan has pioneered this concept, and large-scale field and centrifuge testing are presently being conducted by Nikken Sekkei Nakase Geotechnical Institute.



Basic SMW Treatment Pattern on Land

Basic CDM Treatment Pattern in Marine Conditions

Figure 4. Basic deep mixing treatment patterns (Yang, 1997). (Note: Single columns can also be prodı

Table 1. Techniques used for soil treatment, improvement, and reinforcement (CDM Association, 1996).

Method			Applicable ground				Effects of method						
							Measures against settlement		Measures for stability				
			Clayey soil	Sandy soil	Alteration	Problem soil	Acceleration of consolidation and settlement	Reduction of settlement	Restraint of shear deformation	Acceleration of increase in strength	Addition of resistance	Prevention of liquefaction	Cut-off
Surface soil stabilization		Surface drain method Sand mat method Fabric sheet reinforcement method Surface soil stabilization by hardening agent	x			x			x	x	x	x	
Replacement method		Replacement method by excavation Displacement method	x		x	x		x	x		x	x	
Counter weight fill method		Counter weight fill method Extra fill method at slope	x		x	x			x		x	x	
Consolidation and dewatering	Gradual loading method	Gradually increasing loading method Step loading method	x		x	x			x				
	Surcharge method	Direct surcharge method Vacuum consolidation method Dewatering method	x		x	x	x			x			
	Vertical drain method	Sand drain method Cardboard or plasticboard drain method	x		x	x	x		x	x			
Compaction of	Sand compaction pile method	Sand compaction pile method	x	x	x	x	x	x	x		x	x	
	Compaction method by vibration	Vibroflotation method		x				x			x	x	
Solidification method		Deep mixing method of soil stabilization (CDM method)	x	x	x	x		x	x	x	x	x	x
Mechanical reinforcement method		Mechanical reinforcement method by sheet pile Mechanical reinforcement method by pile driving Mechanical reinforcement method by slab Mechanical reinforcement method by culvert	x	x	x	x		x	x		x		x

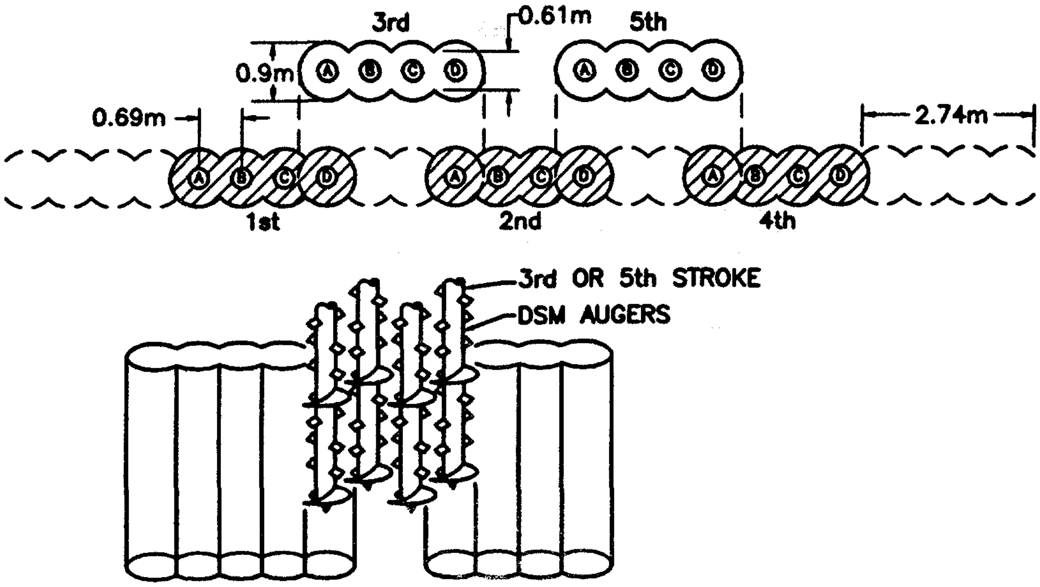


Figure 5. DMM installation sequence (Bahner and Naguib, 1998).

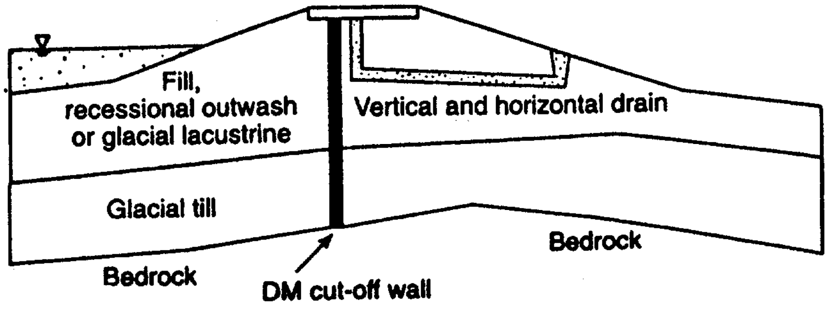
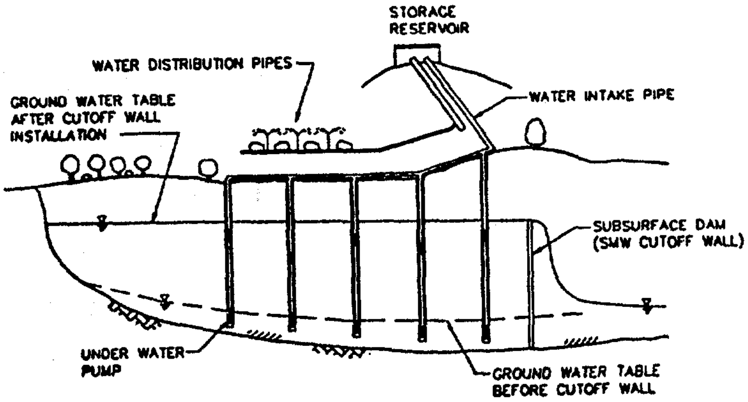
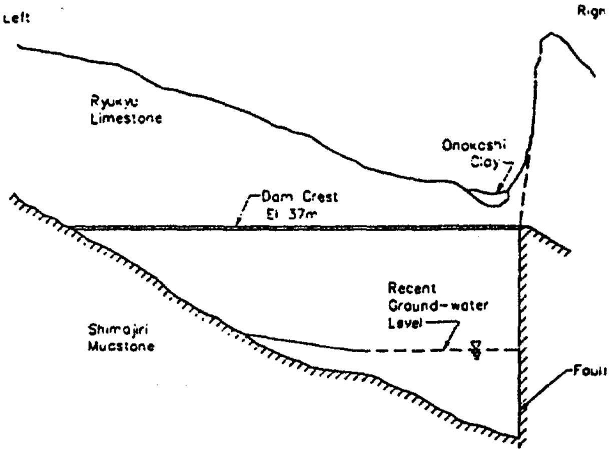


Figure 6. Cushman Dam rehabilitation project, WA, U.S.A. (Yang and Takeshima, 1994).



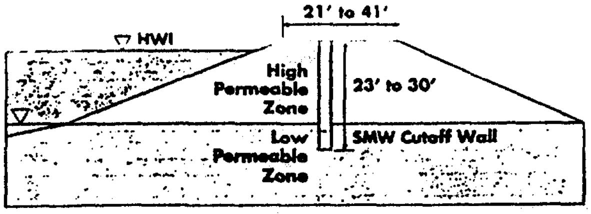
(a)

Schematic of Subsurface Dam
(after Nikkei 1990)



(b)

Sunagawa Subsurface Dam
Okinawa, Japan
(after Kyushu, 1992)



(c)

Levee Cross Section

Sacramento Levee Reconstruction
Sacramento, CA

Figure 7. Examples of DMM cut-off walls (Yang, 1997).
(1 ft = 0.305 m)

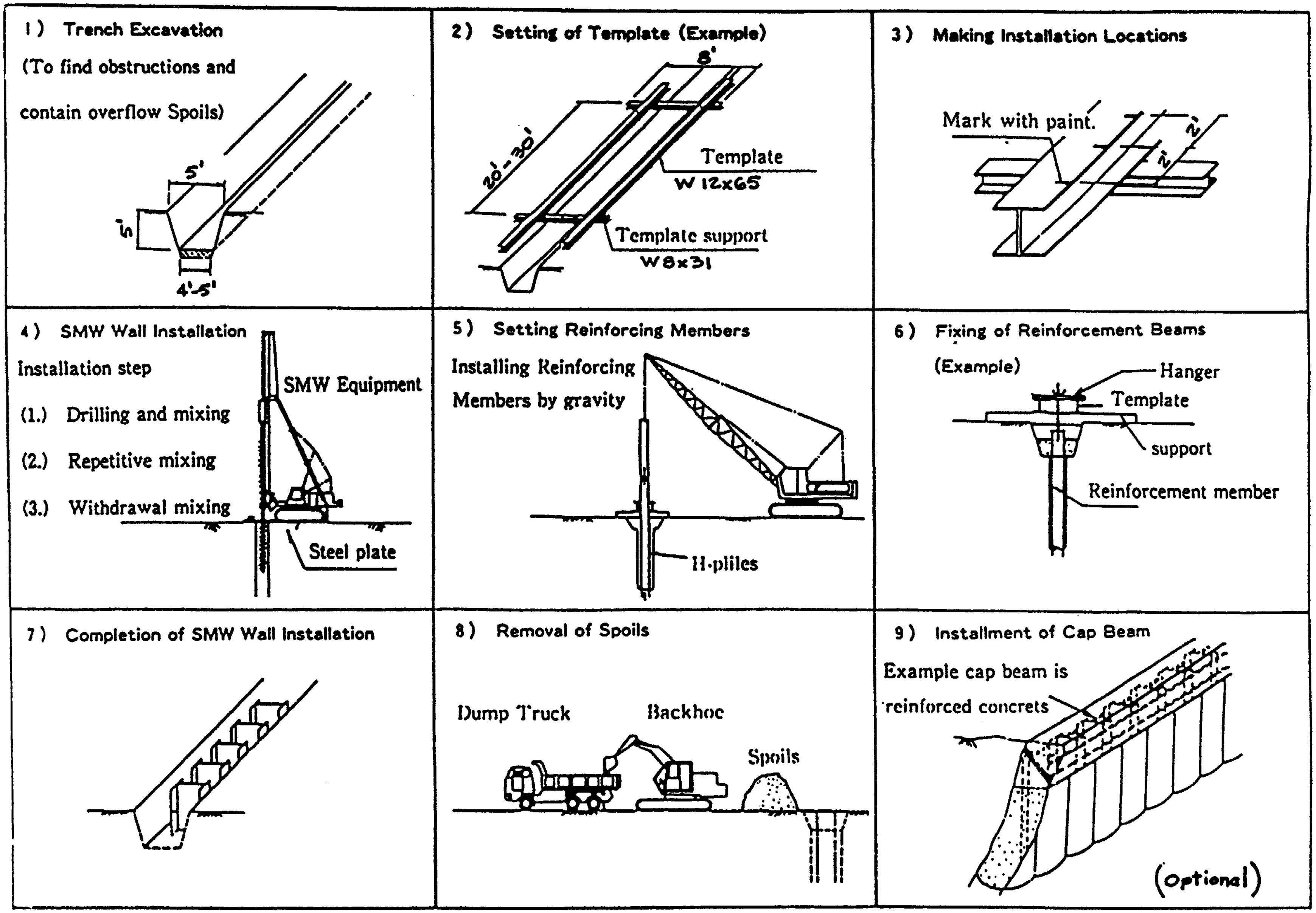


Figure 8. Construction steps for DMM used to create excavation support (Pearlman and Himick, 1993).
(1 ft = 0.305 m)

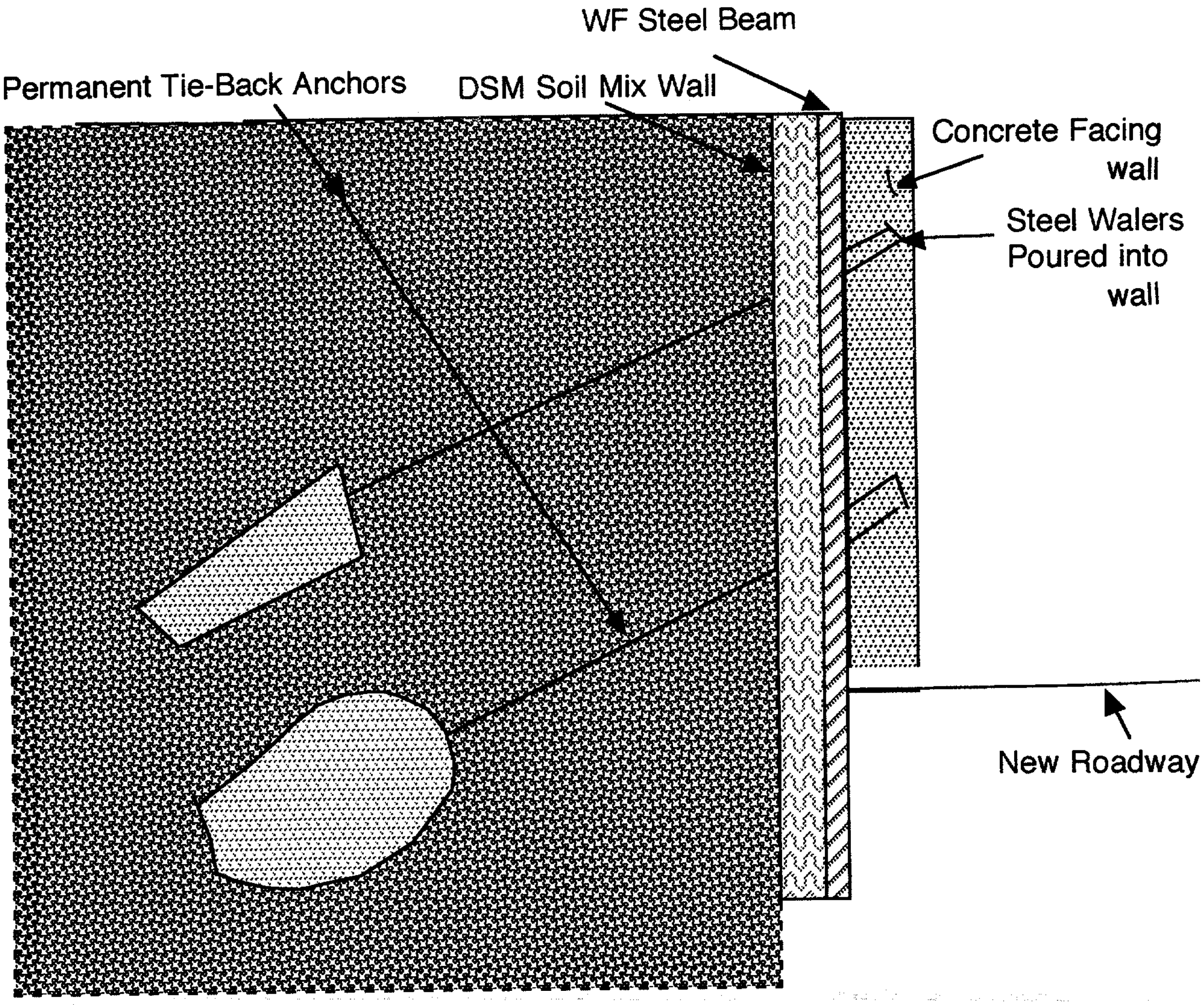


Figure 9. Cross section: Lake Parkway, Milwaukee, WI (Geo-Con, Inc., 1998).

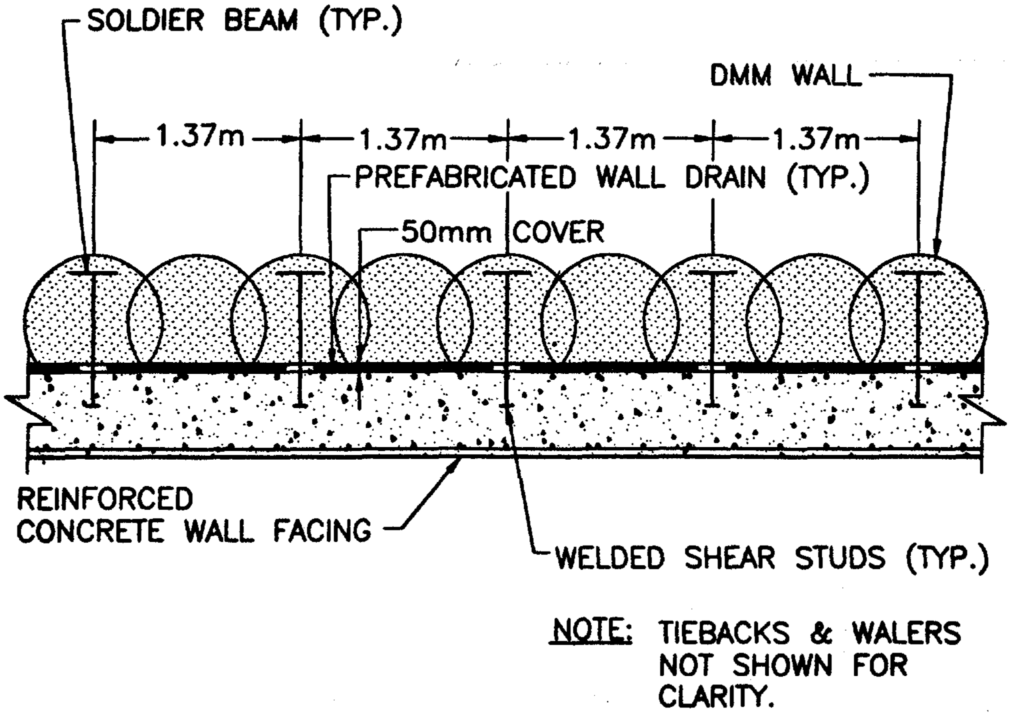
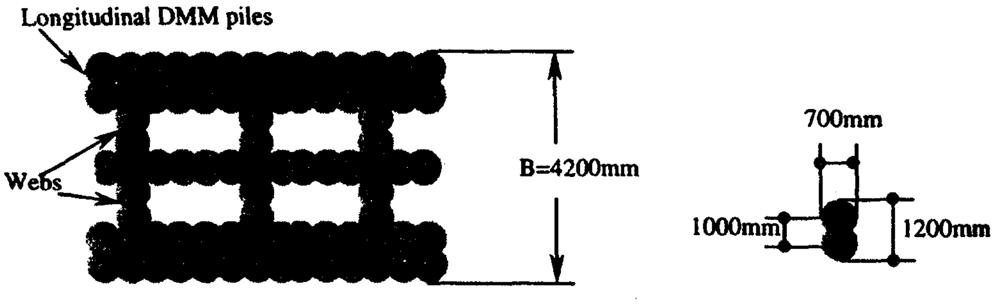


Figure 10. Plan view, DSM wall, concrete facing and tieback anchors, Lake Parkway, Milwaukee, WI (Bahner and Naguib, 1998).



(a) DMM Retaining Walls

(b) Single DMM Pile

Figure 11. Plan of DMM retaining structure (Shao et al., 1998).

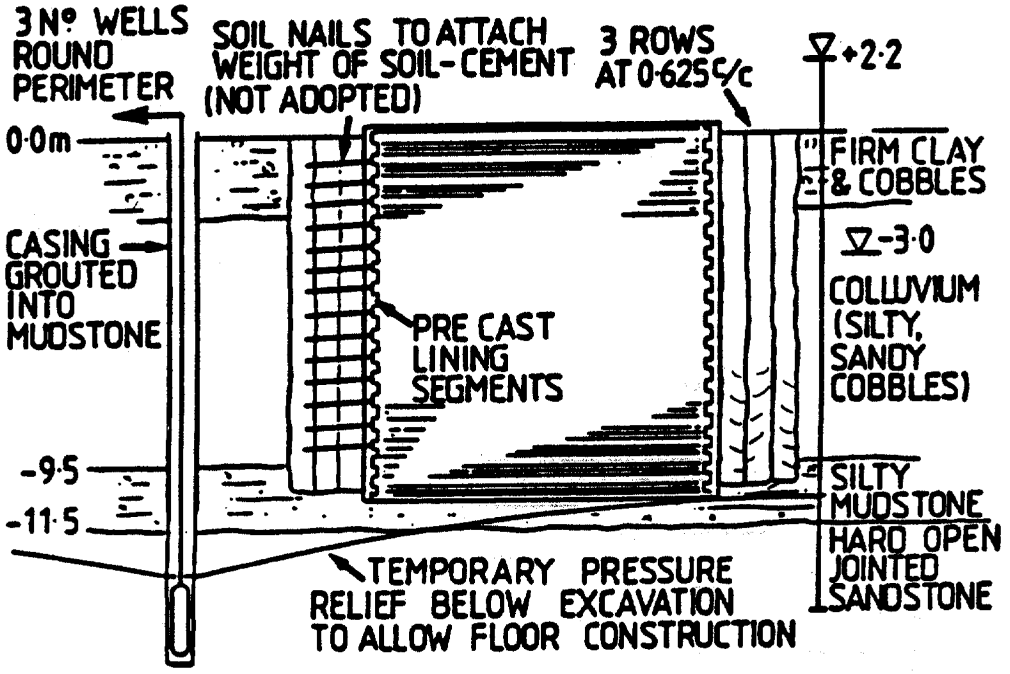


Figure 12. Details of circular shaft constructed with DMM in England (Elliott, 1989) (after Greenwood, 1988).

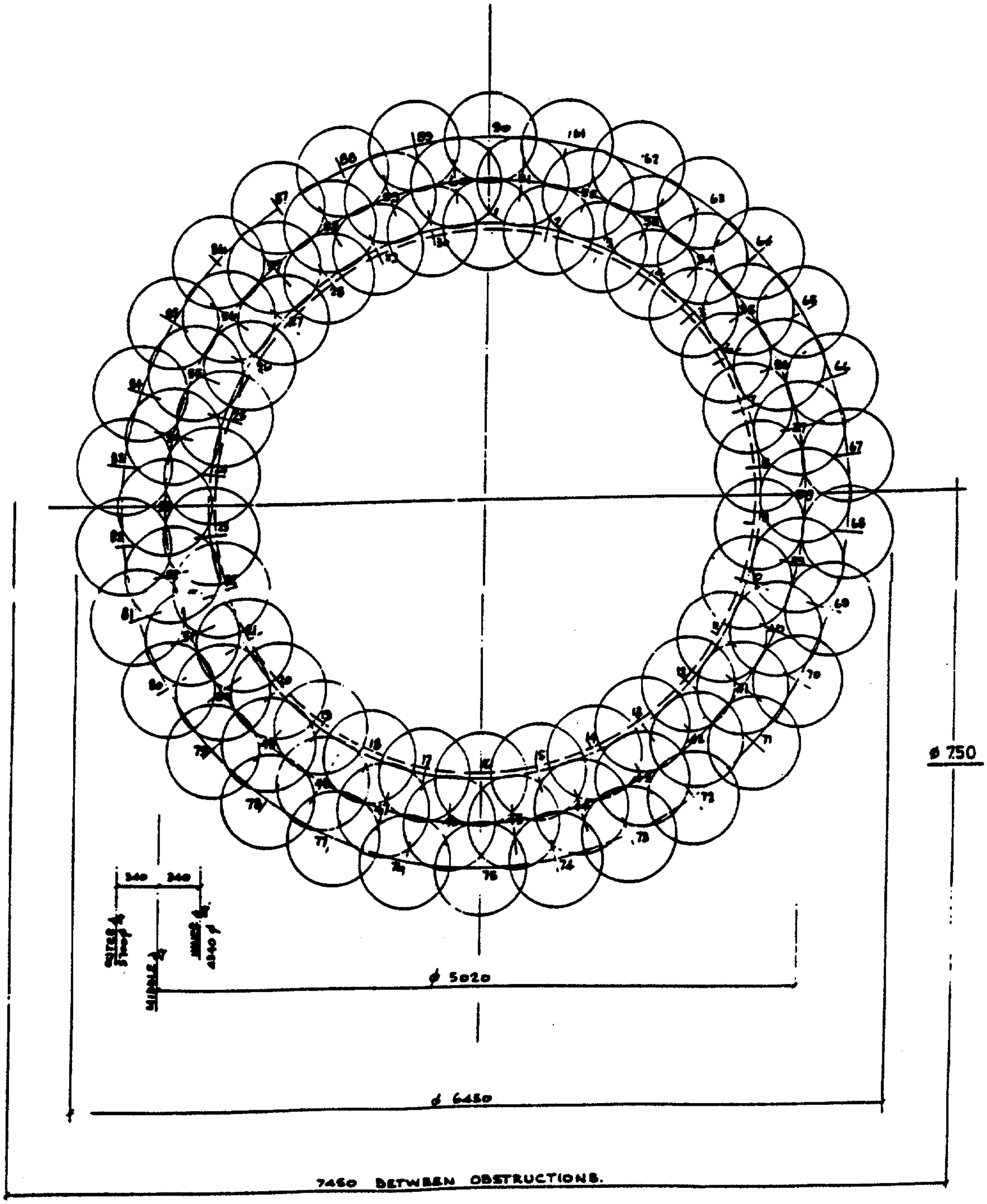


Figure 13. Another circular shaft constructed with DMM in England (Blackwell, 1992).

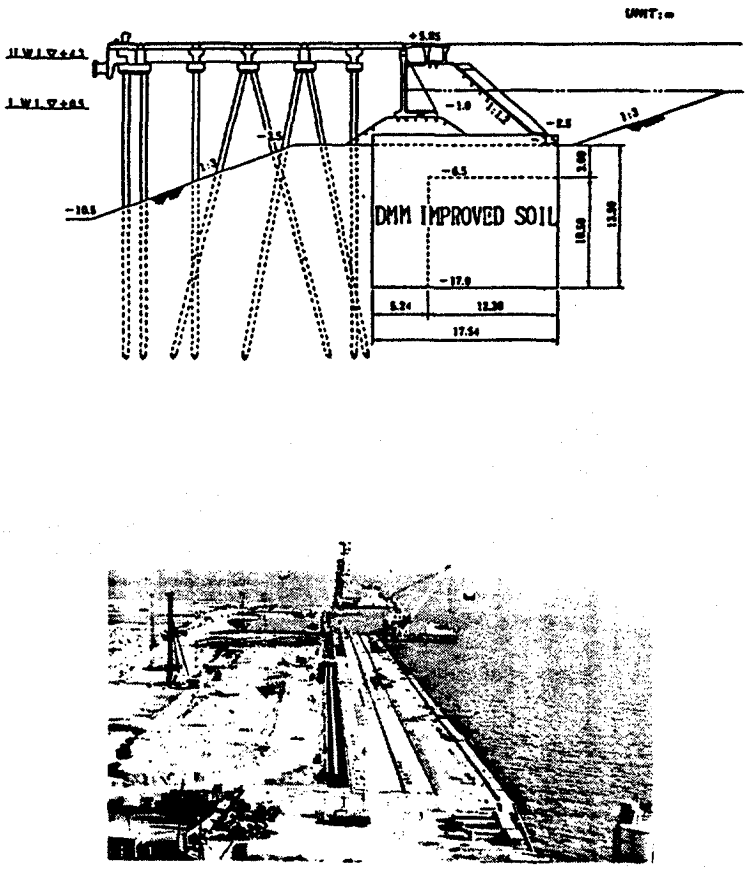


Figure 14. Standard cross section of the Southern Wharf and photograph of construction, Tianjin, China (Hosomi et al., 1996).

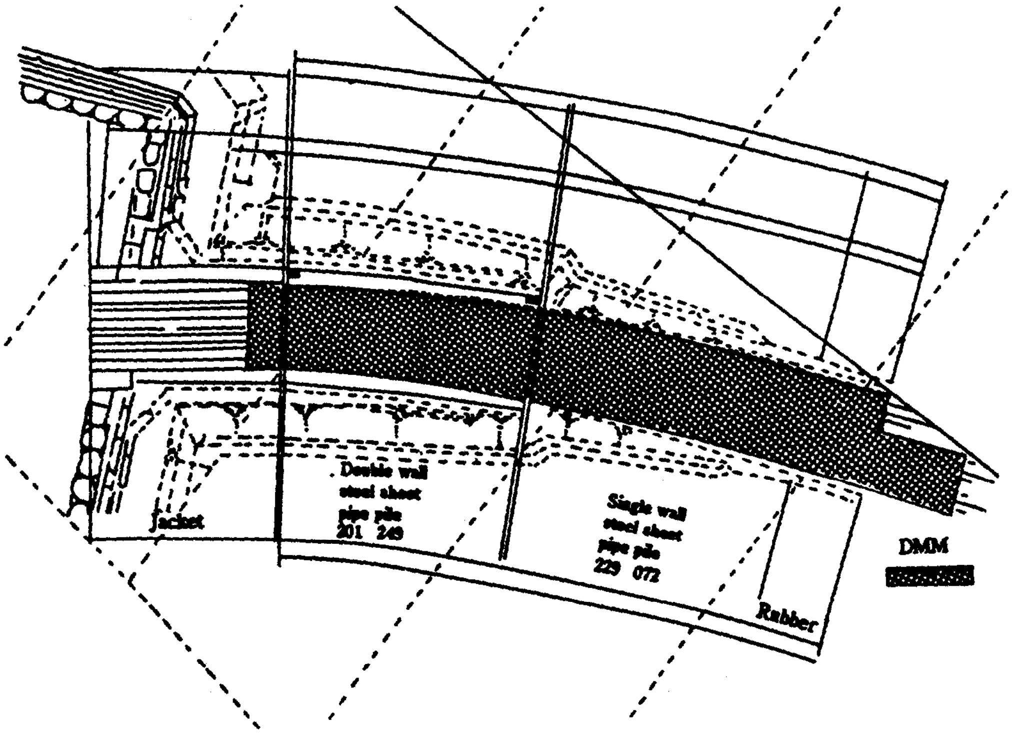


Figure 15. Plan of DMM work, Trans-Tokyo Bay Tunnel (Unami et al., 1996).

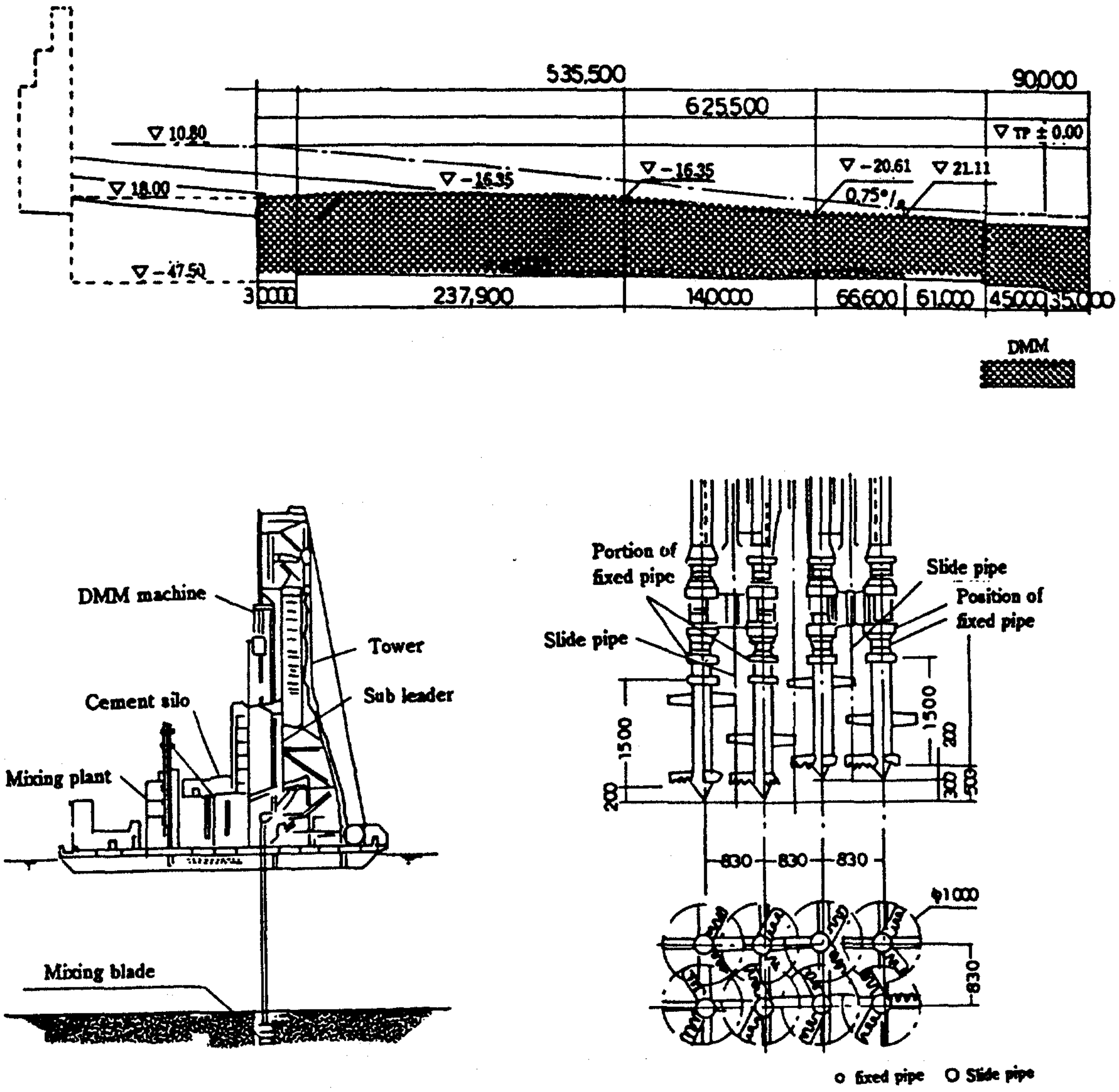
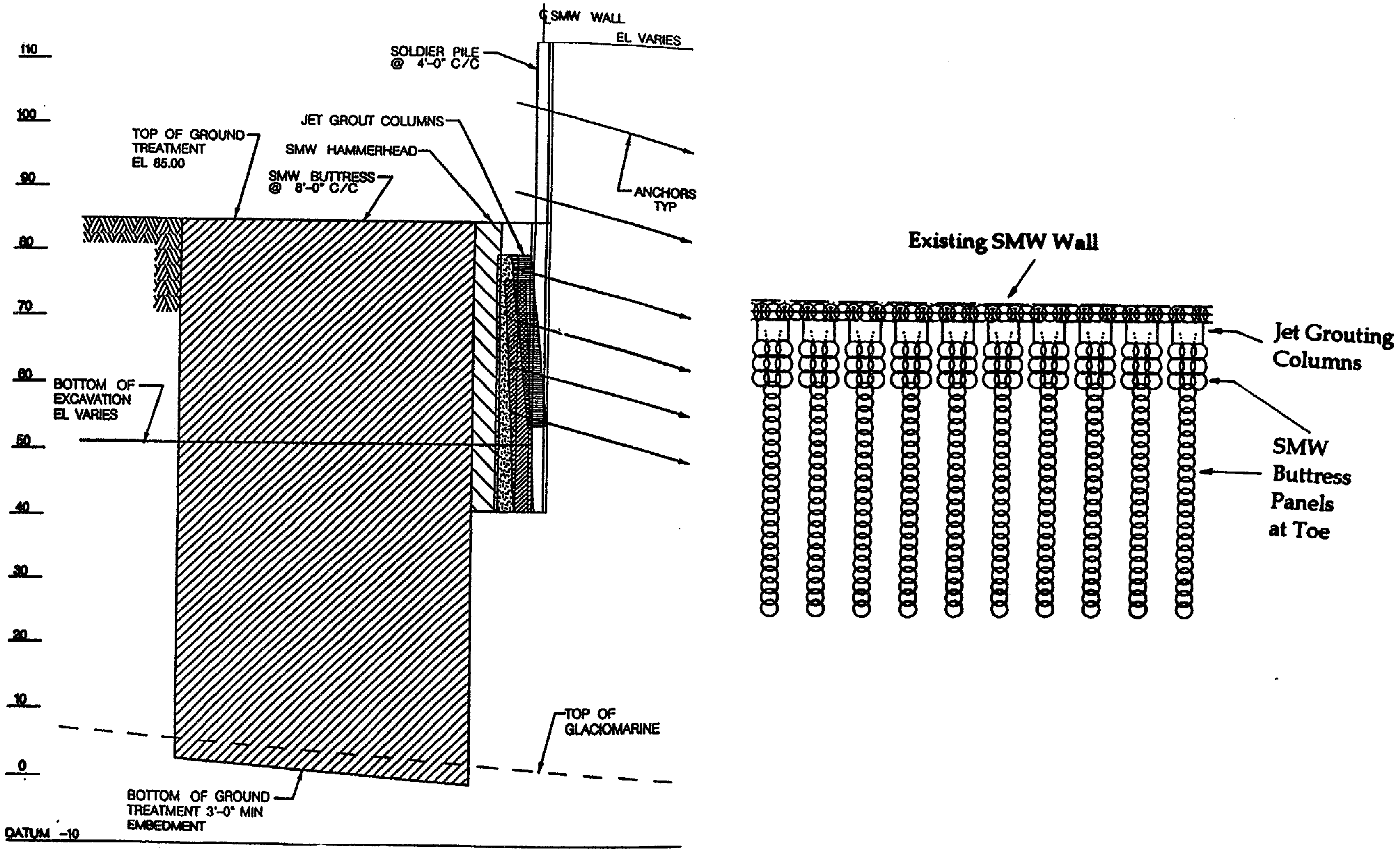


Figure 16. Elevation of DMM work and details of mixing equipment (Unami et al., 1996).



EAST WALL
DEEP SMW BUTTRESS FOUNDED IN GLACIOMARINE

Figure 17. DMM used at Contract C07A, CA/T, Boston, MA (Nicholson and Chu, 1994).
(1 in = 25.4 mm, 1 ft = 0.305 m)

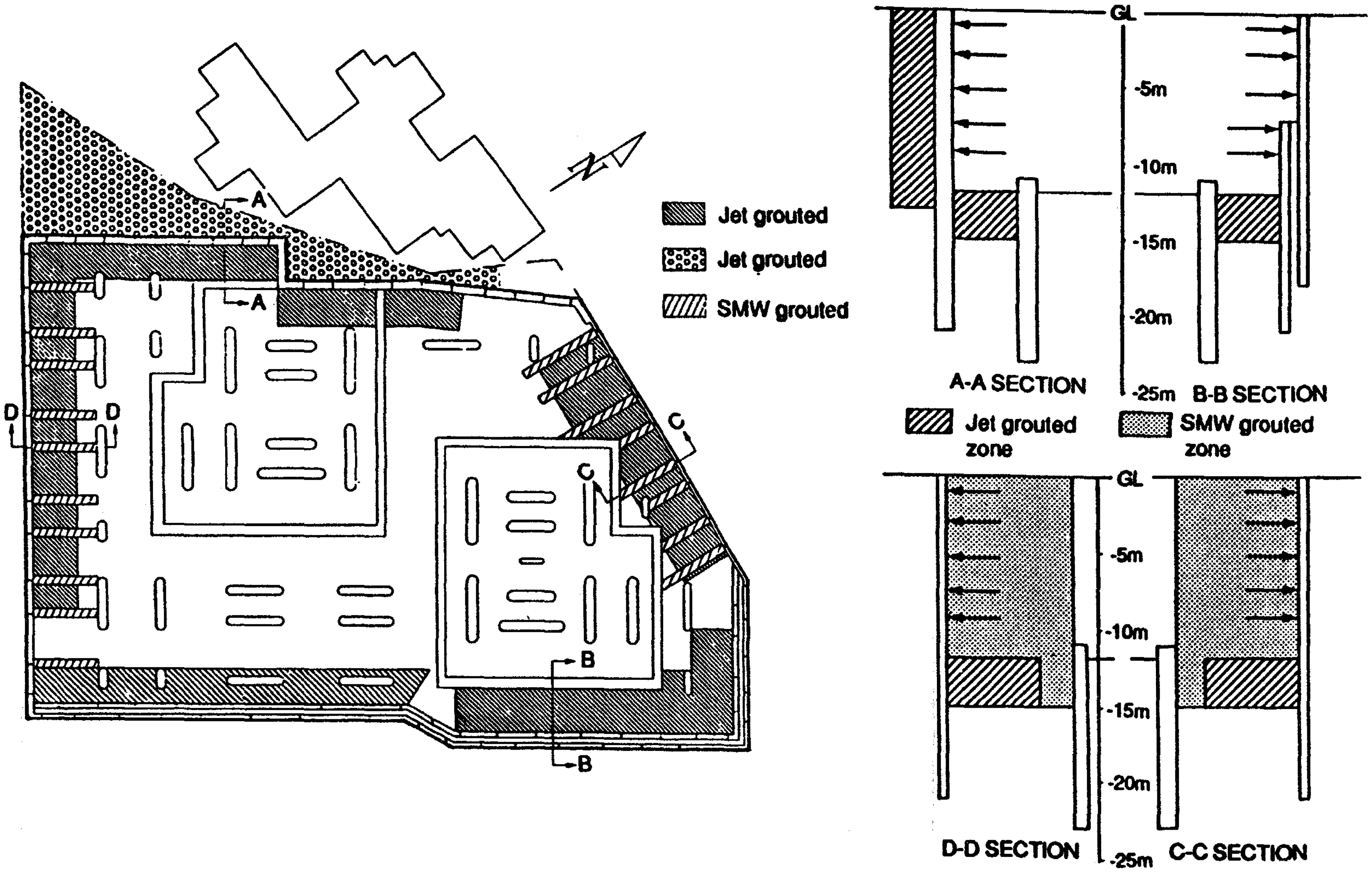


Figure 18. Layout of DMM buttress treatment, Taipei (Liao et al., 1992).

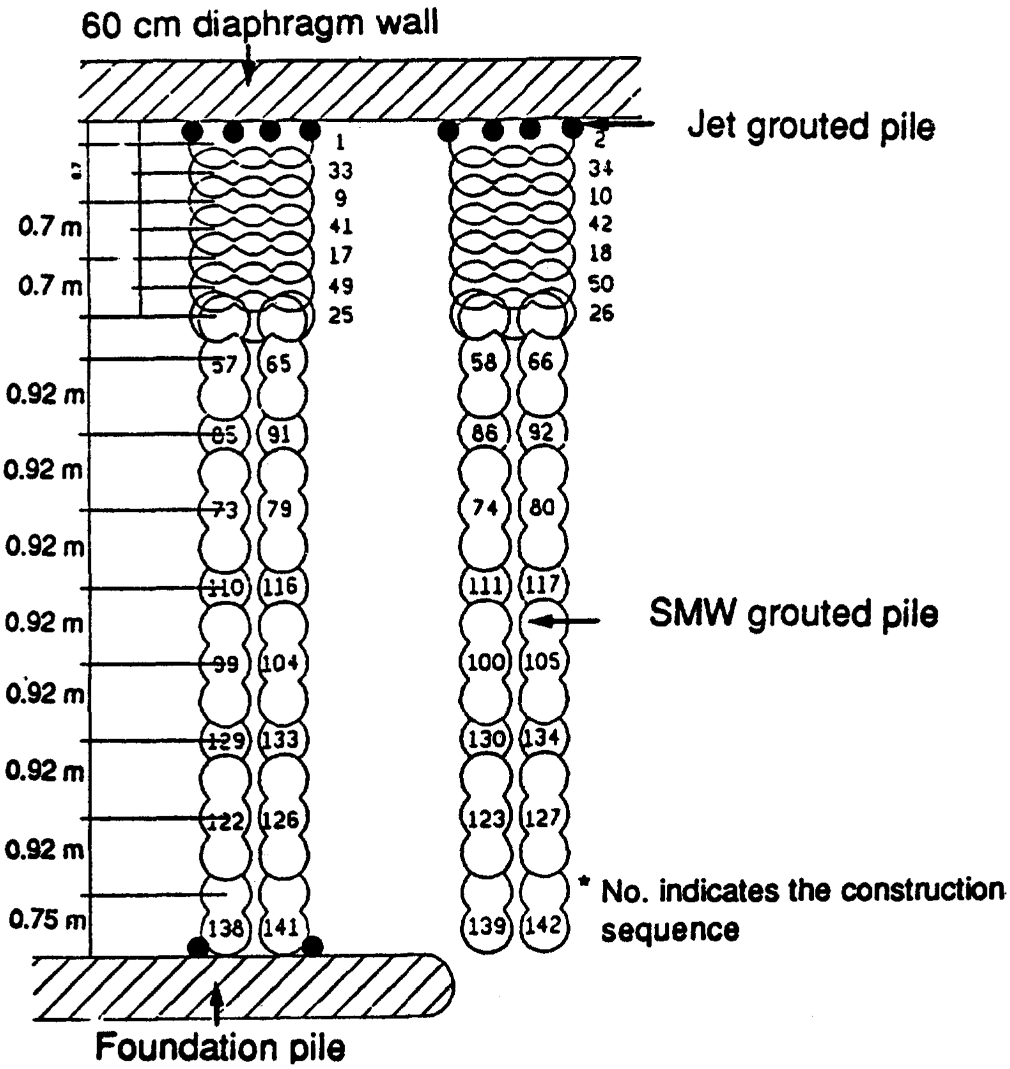
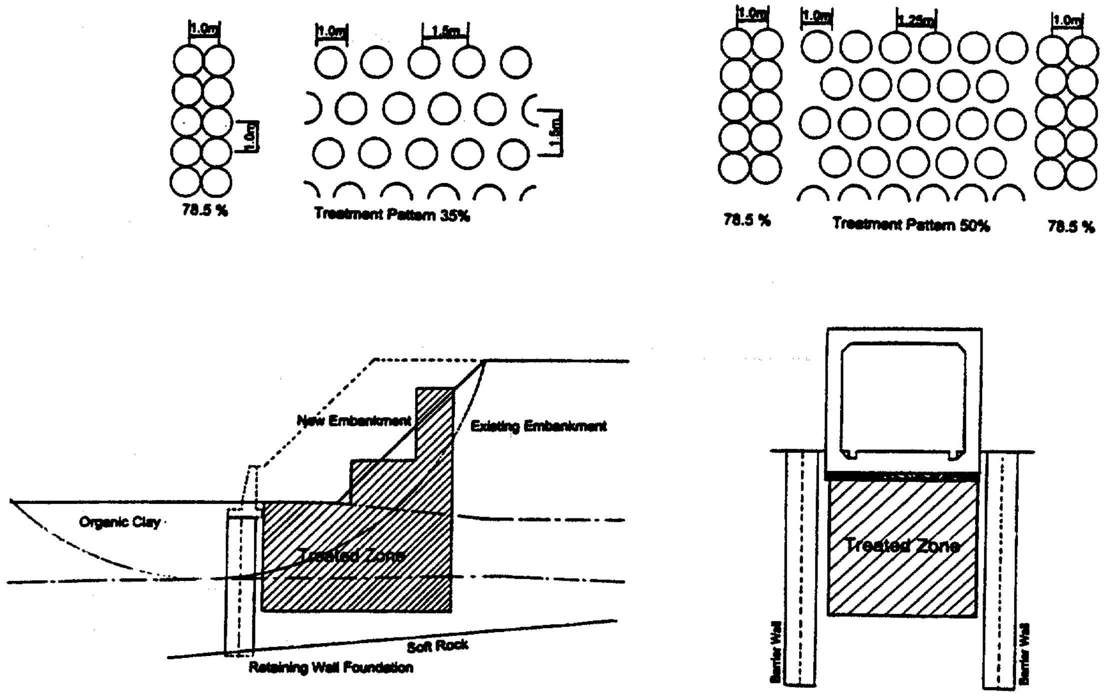


Figure 19. Plan of DMM buttress treatment, Taipei (Liao et al., 1992).



a) Embankment Foundation

b) Culvert Foundation

Figure 20. Cross sections and treatment patterns, Tomei Freeway, Japan (Yang et al., 1998).

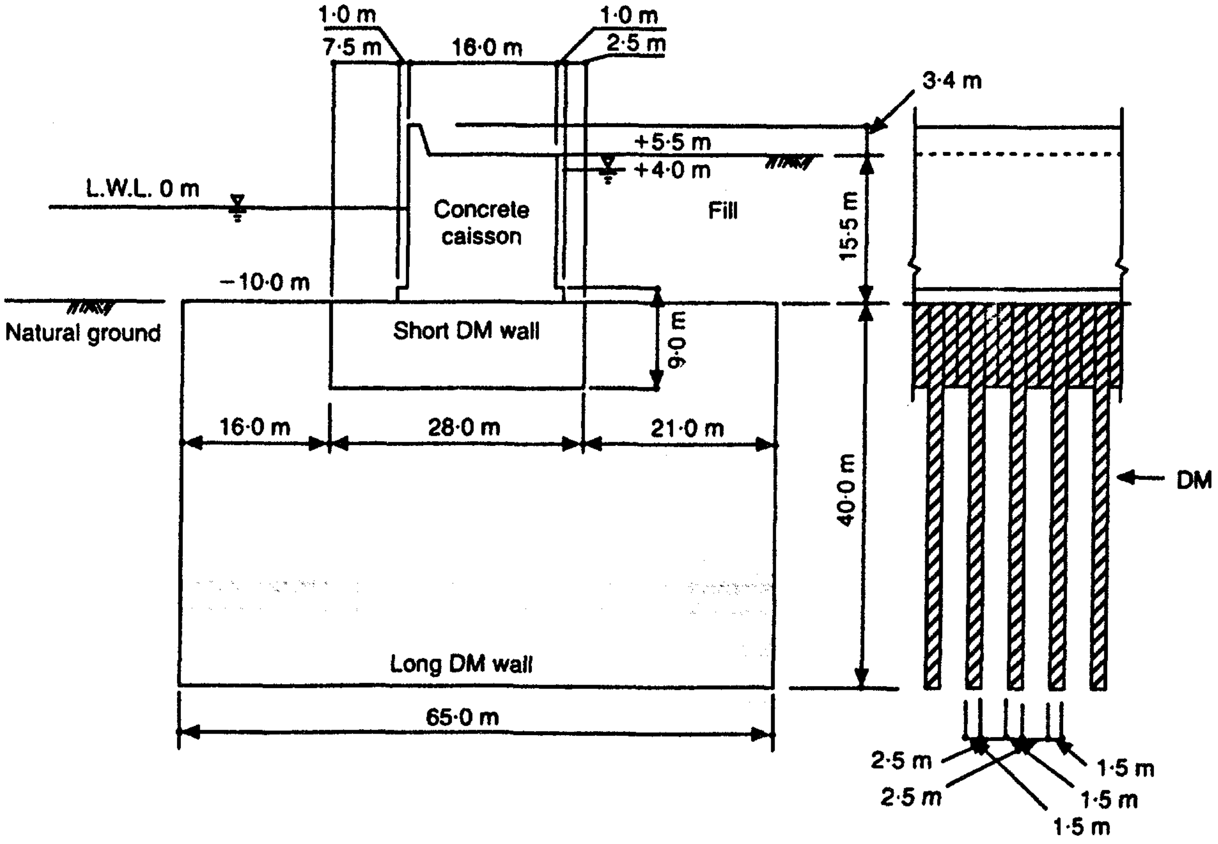


Figure 21. Design section for quay wall for a waste disposal plant, Japan (Kawasaki et al., 1981).

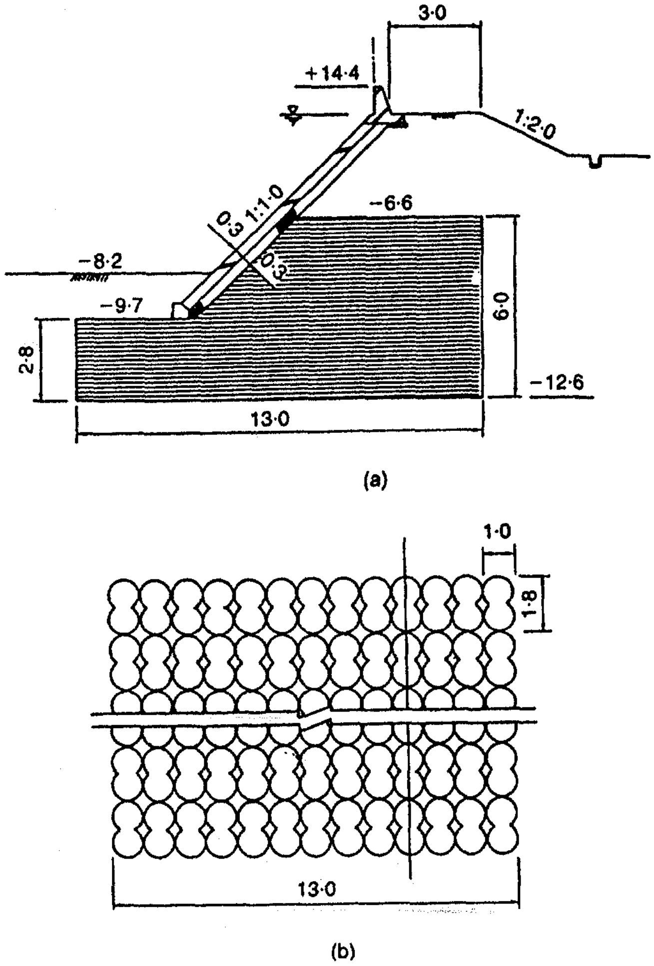


Figure 22. Stabilization of a river bank slope in Japan: (a) cross section, (b) plan of improved zone (dimensions in meters) (CDM Association, 1994).

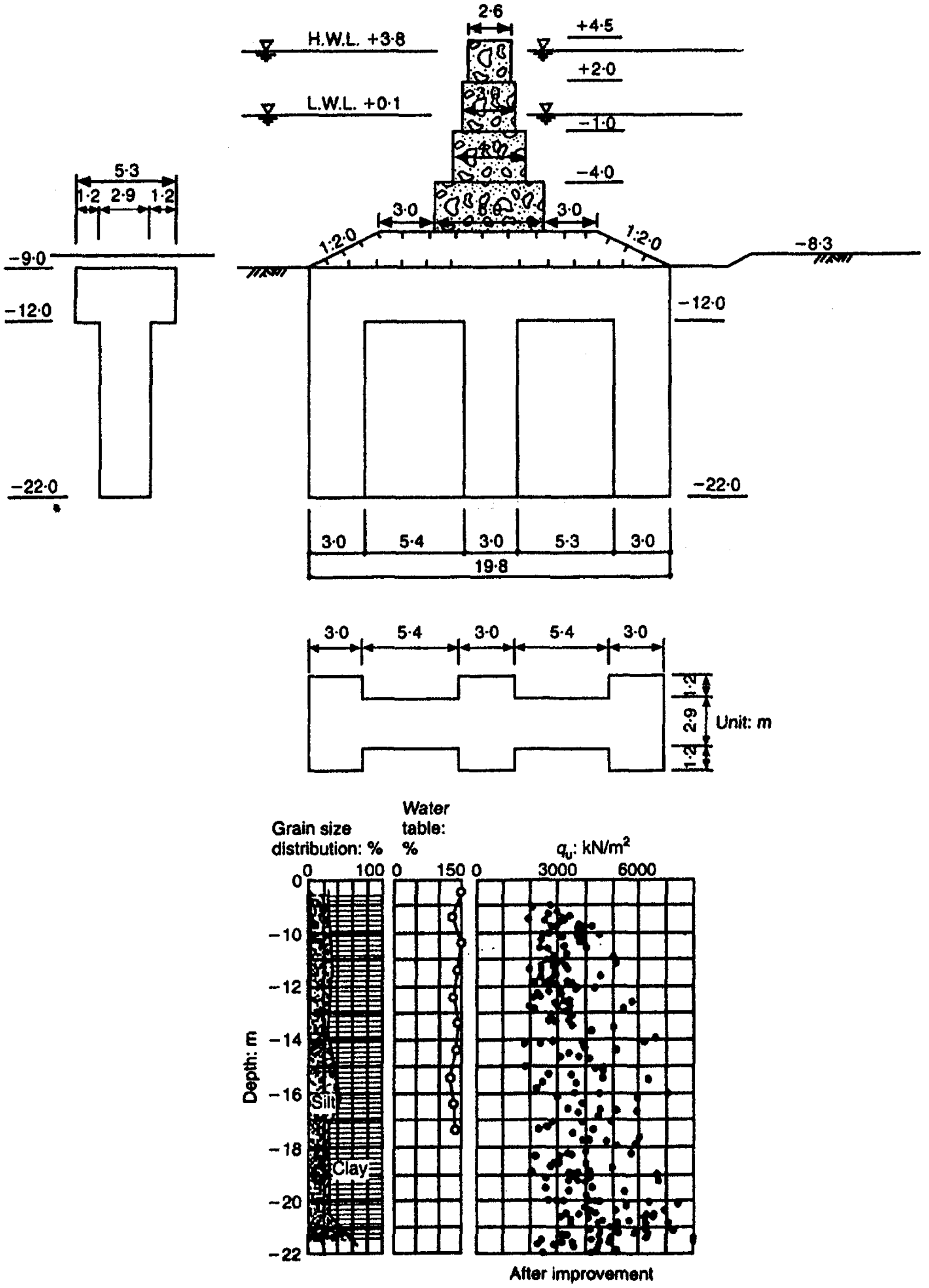


Figure 23. Breakwater designed for Hiroshima, Japan (CDM Association, 1994).

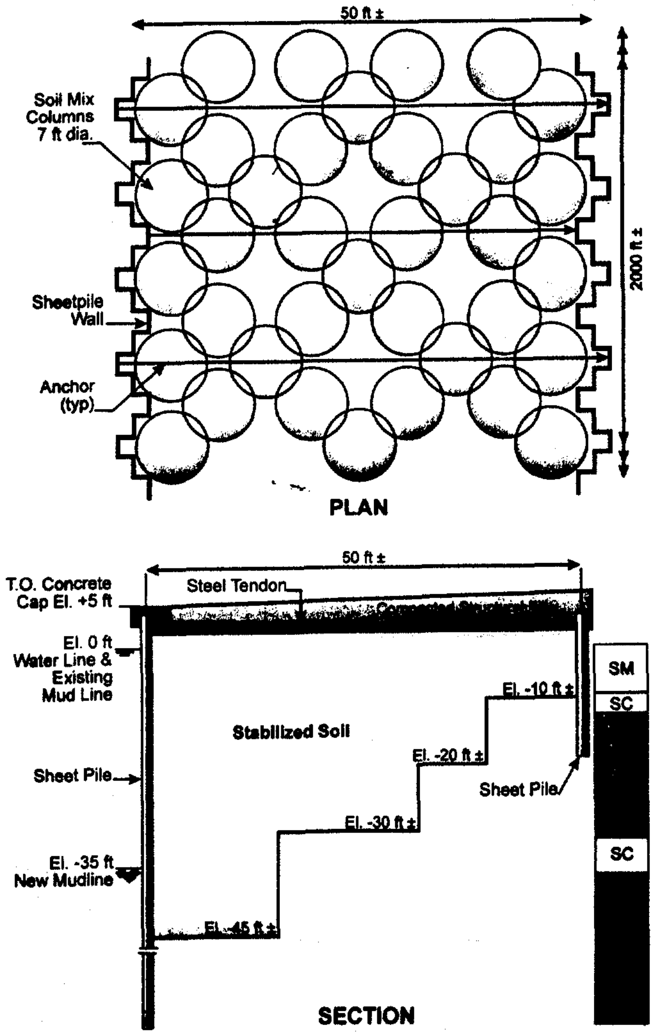
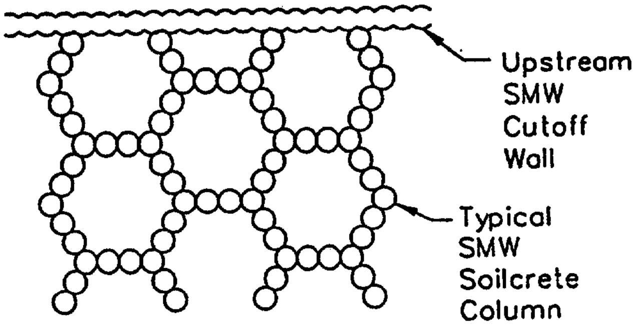


Figure 24. Column layout and cross section of the stabilization of a waterfront birthing and unloading facility in Pascagoula, MS (Hayward Baker, Inc., 1998). (1 ft = 0.305 m)



SMW Treatment Pattern
Jackson Lake Dam Project
Wyoming

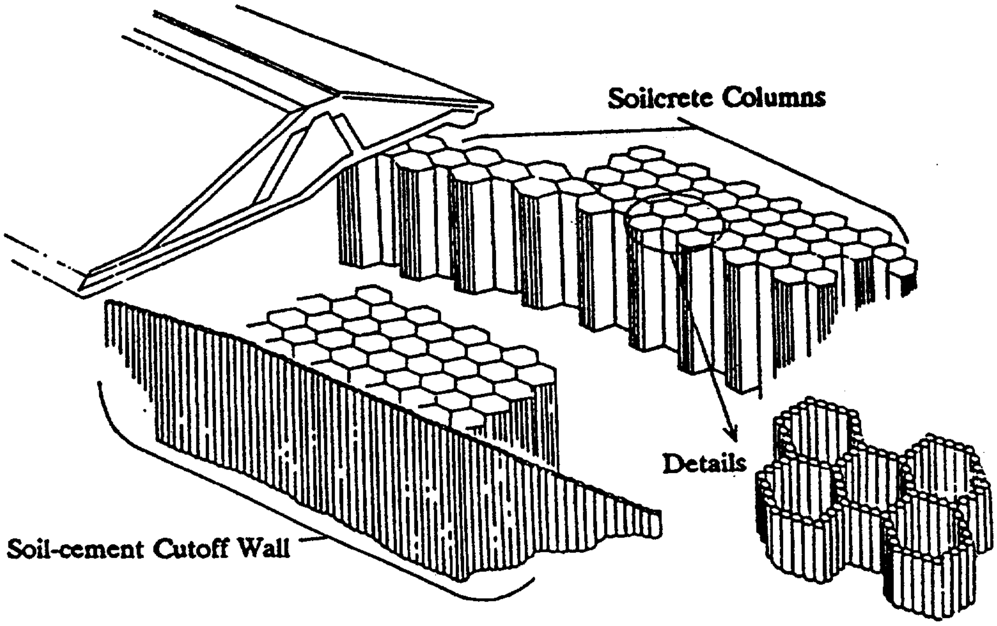


Figure 25. DMM used for liquefaction control and seepage cut-off, Jackson Lake Dam, WY (Taki and Yang, 1991).

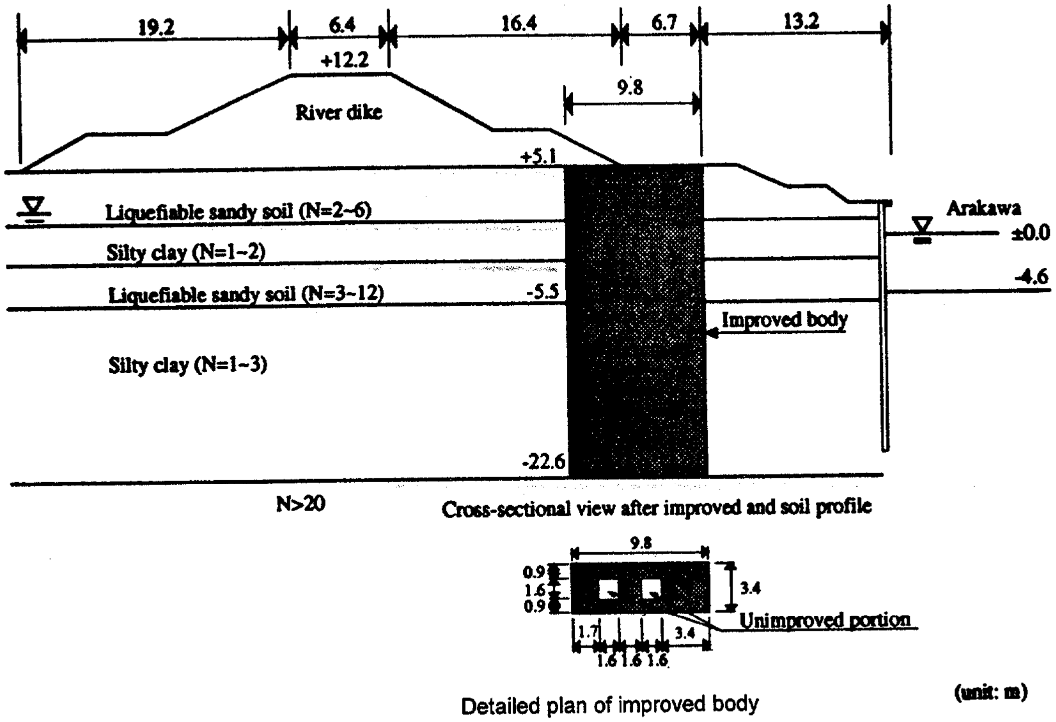
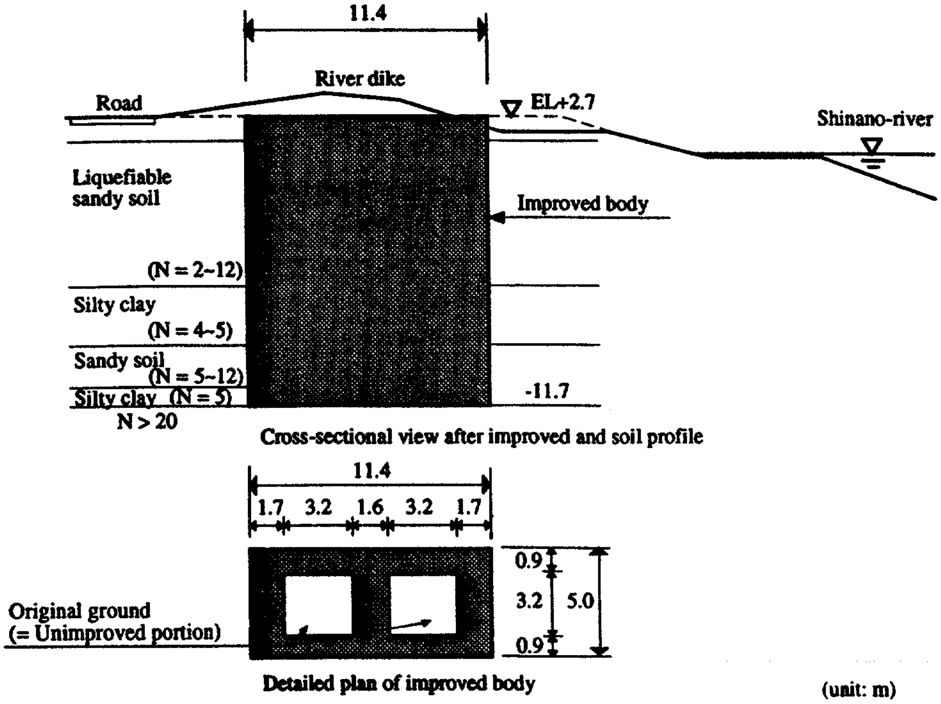
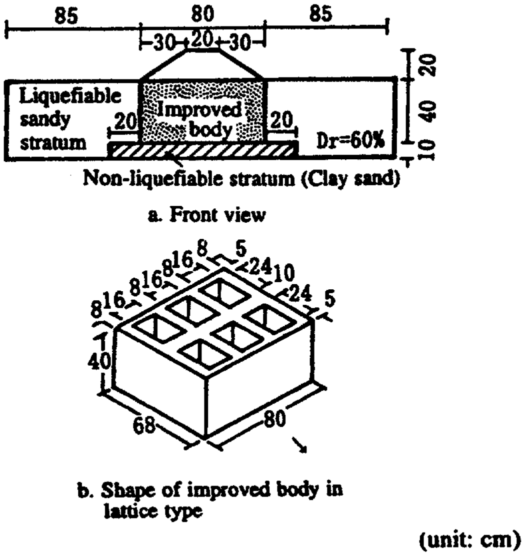


Figure 26. DMM lattices at the Arakawa River dike, Japan (Matsuo et al., 1996).



Cross-sectional view after improved and soil profile

Detailed plan of improved body



a. Front view

b. Shape of improved body in lattice type

Figure 27. DMM lattices at the Shinano River dike, Japan (Matsuo et al., 1996).

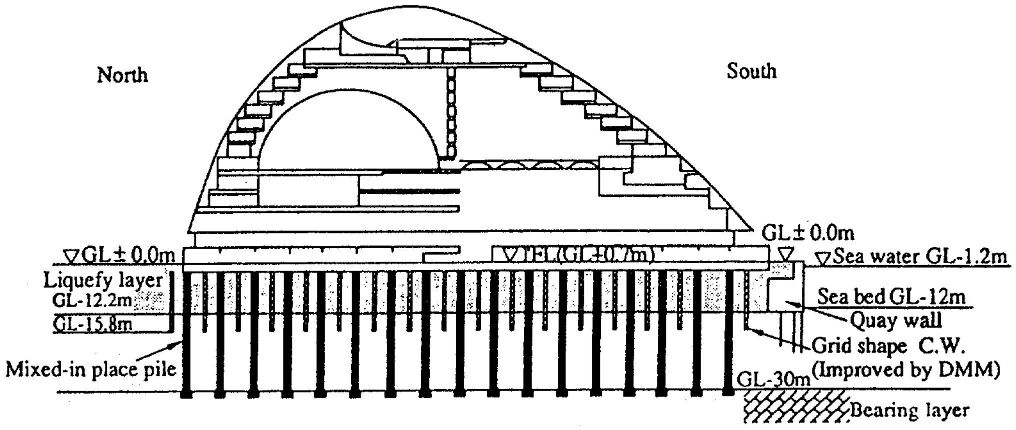
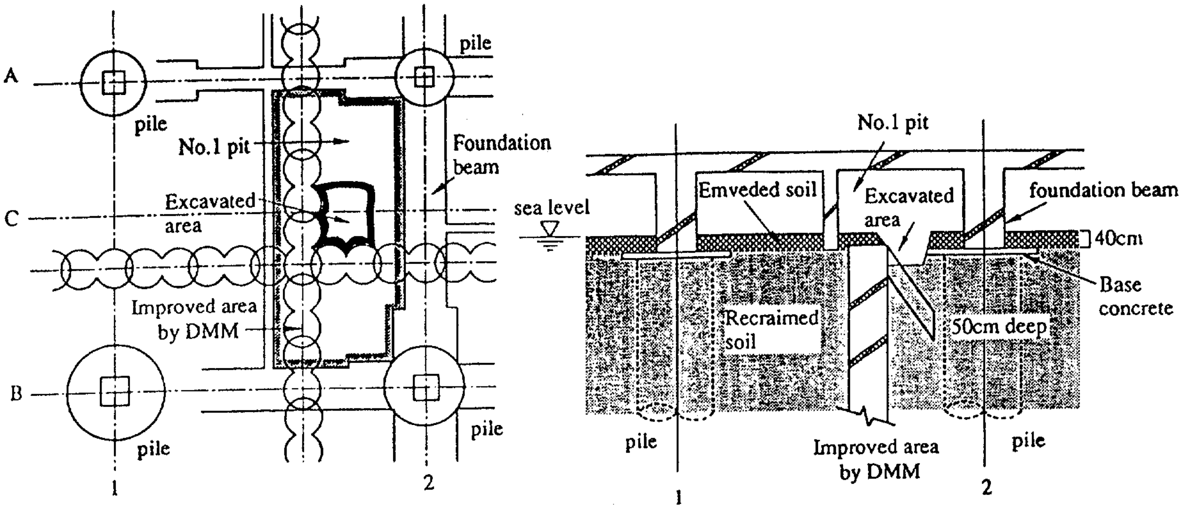


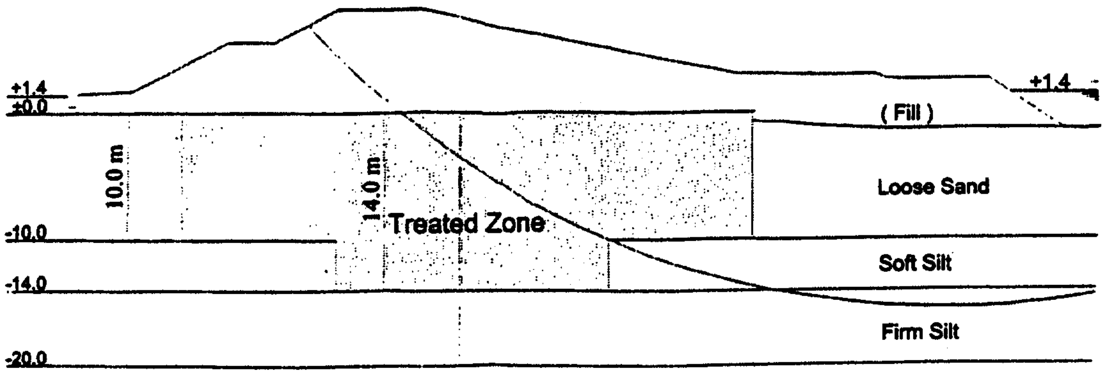
Fig. 24 Cross-section of the building structure and foundation



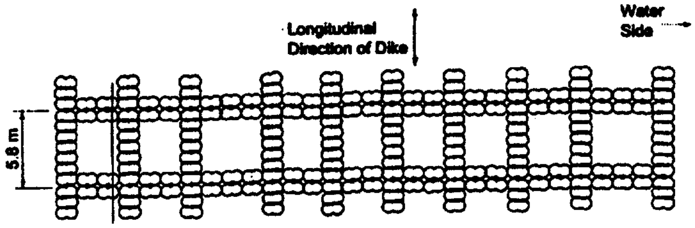
(a) Plan of excavated area

(b) Cross- section of C- line

Figure 28. Details of the DMM used under the hotel and terminal building, Kobe, Japan (Kamon, 1996).

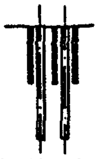
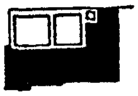


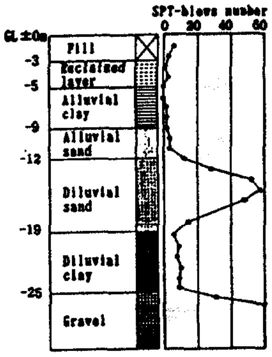
a) Dike Cross Section



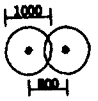
b) Modular Grid

Figure 29. Reconstruction of Torishima Dike with DMM grids following the Kobe earthquake, 1995 (Yang et al., 1998).

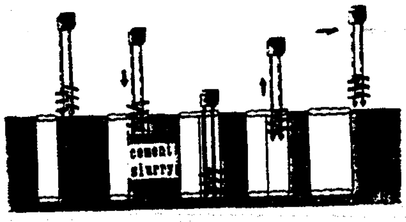
Type	A	B	C	D	
Cross Section	 Section A	 Section B	 Section C	 Section D	
Application	Reduction of horizontal displacement of pile	Countermeasure against liquefaction	Slope stability Trafficability	Self-supported earth retaining wall	Foundation of structure
qu (MPa)	0.37	1.49	1.49	2.61	1.49



Soil profile

Model	DCM-L5
Type	Electric drive 2-shaft
Motor	75kW-416P duplex type
Revolutions (r.p.m)	24/8P 43/4P
Torque (kN·m)	30/8P 20/4P
Improved area (m^2)	1.50
Overall length (m)	33.85 Effective length:30.0
Weight (kN)	220
Diameter of blade and Distance between axes	 1000 800

Specifications of typical mixing machine



cement slurry

① Positioning the mixing machine
② Penetrating the ground while mixing cement slurry with the soil
③ Mixing at the maximum depth of penetration
④ Withdrawing the blades while mixing cement slurry with the ground
⑤ Completion of withdrawal

Execution procedure

Figure 30. DCM-type DMM used for different applications at the same site, Tokyo, Japan (Babasaki and Suzuki, 1996).

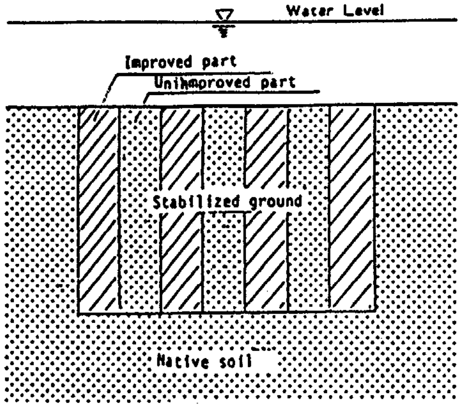
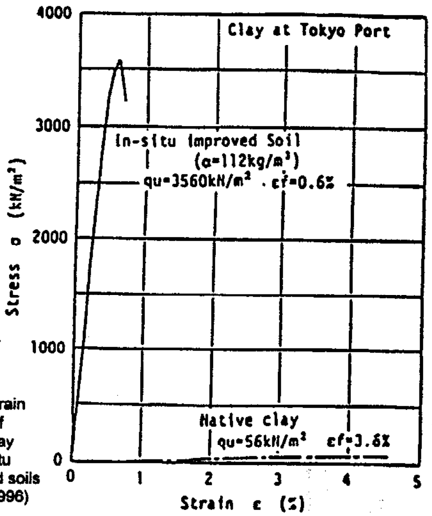
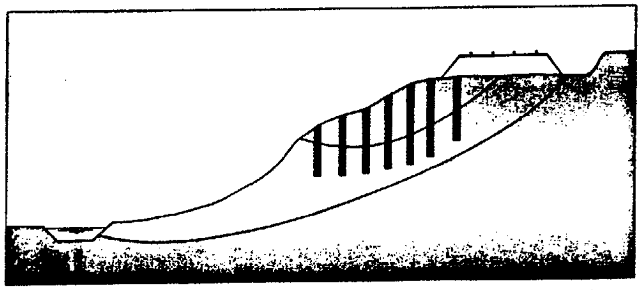


Diagram of stabilized ground

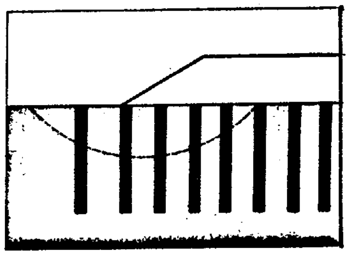
(CDM, 1996)



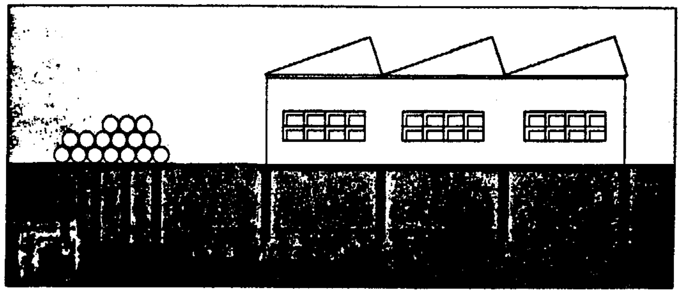
Typical stress-strain curves of native clay and in situ improved soils (CDM, 1996)



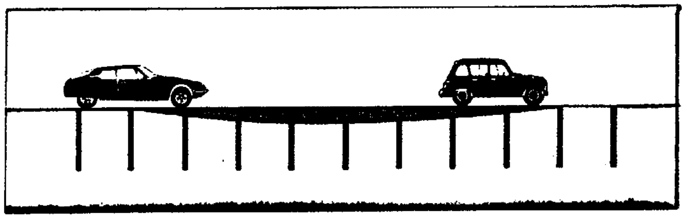
embankment



road embankment



storing yards and light buildings



road bed

Figure 31. Use of DMM as in situ reinforcement (lower diagrams from Bachy literature, 1992).

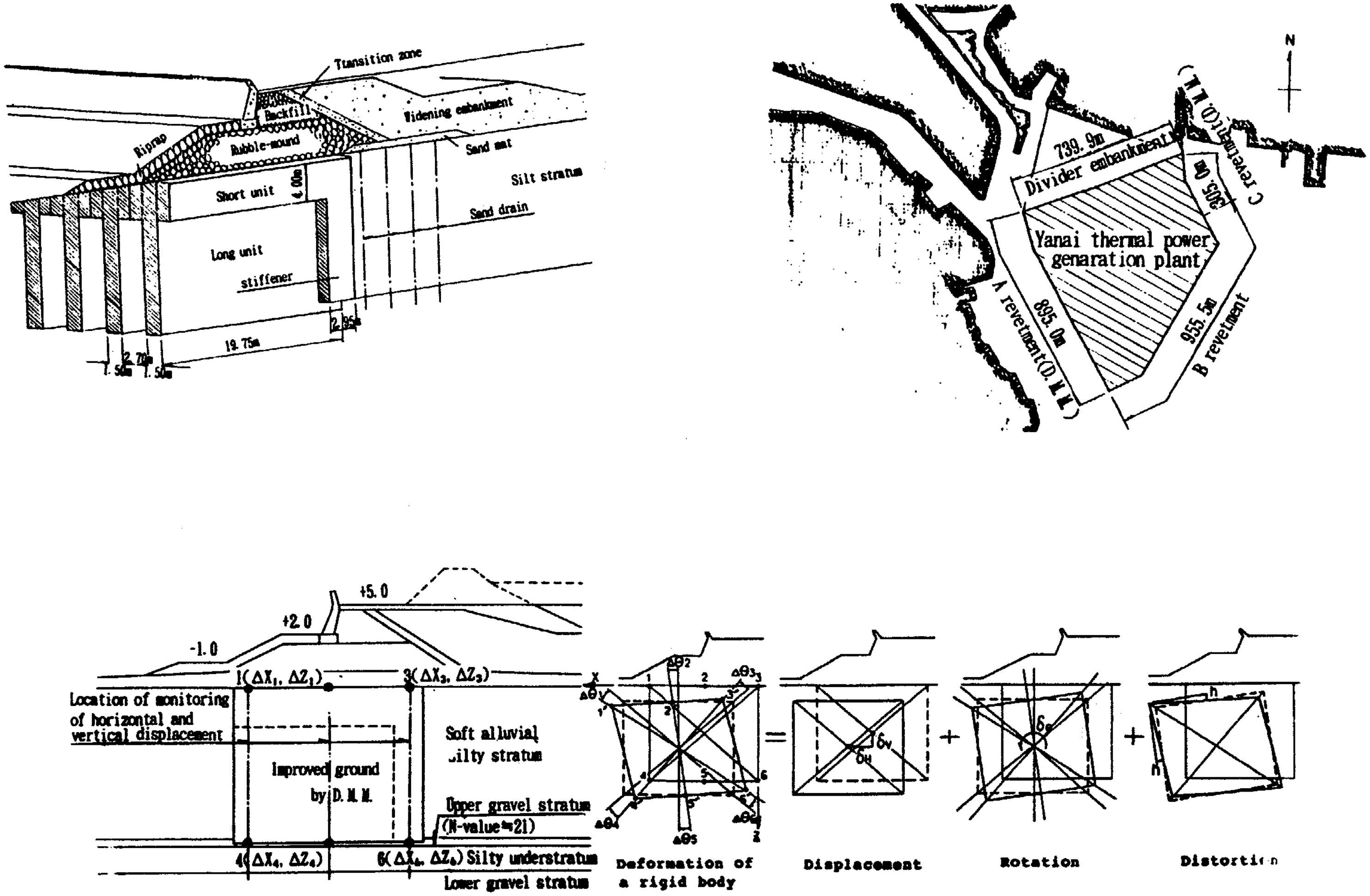


Figure 32. DMM used to create a “floating foundation” at Yanai power station, Japan (Noriyasu et al., 1996).

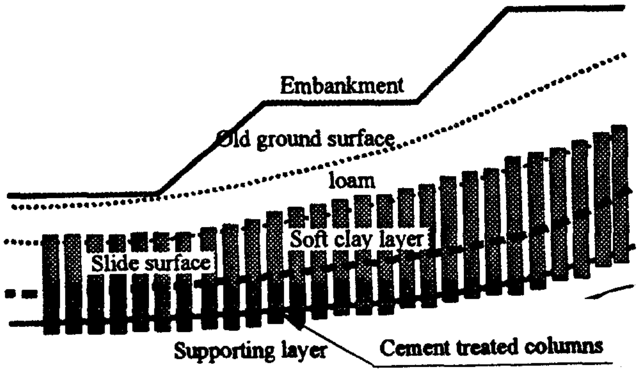


Figure 33. Use of DMM columns for slope stability (Dong, et al., 1996).

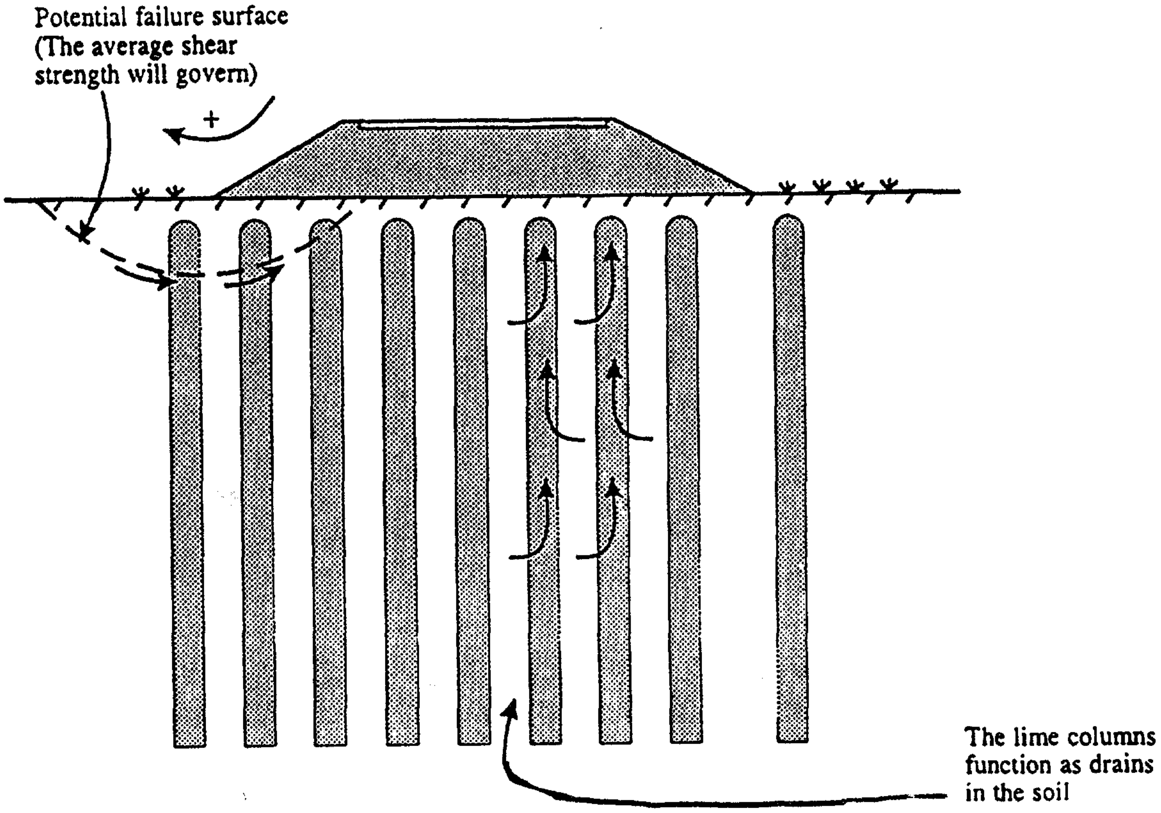


Figure 34. Lime columns used as in situ reinforcement (Stabilator, 1992).

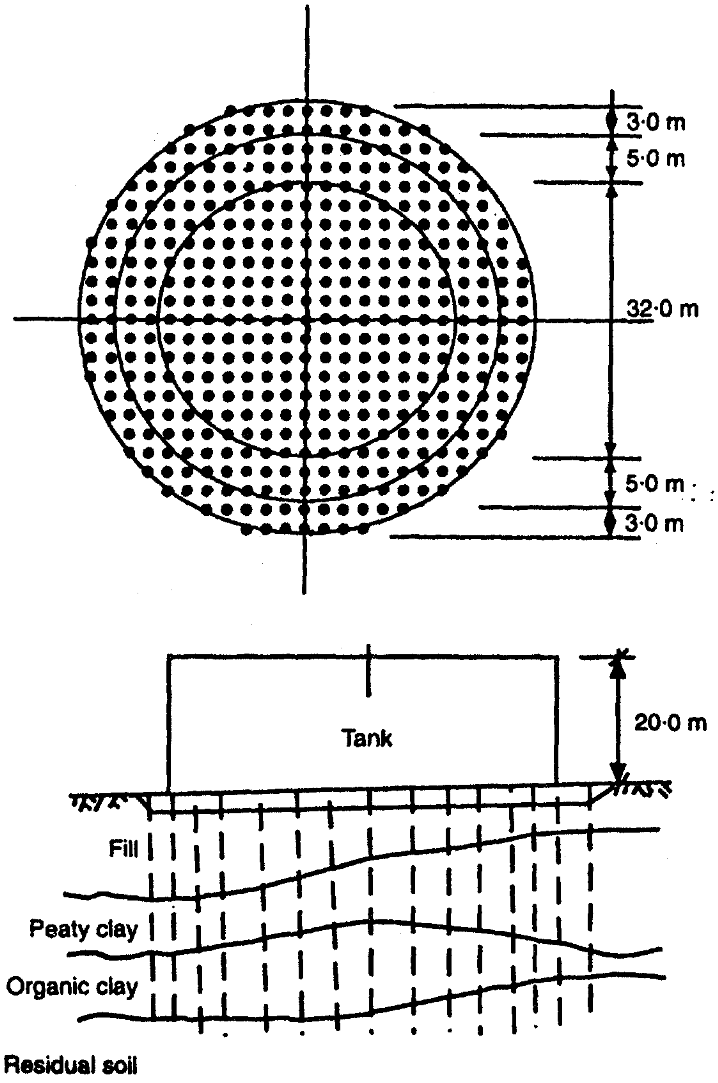


Figure 35. Foundation stabilization for a fuel tank in Singapore (Ho, 1996).

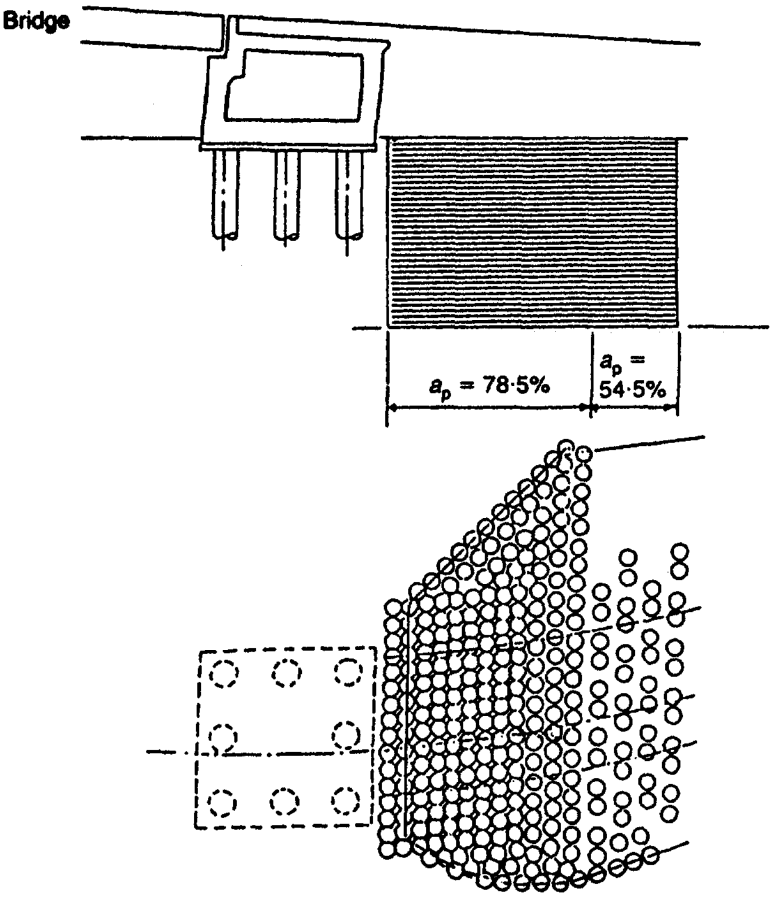


Figure 36. Layout of DJM piles for an abutment of a bridge (DJM Association, 1993).

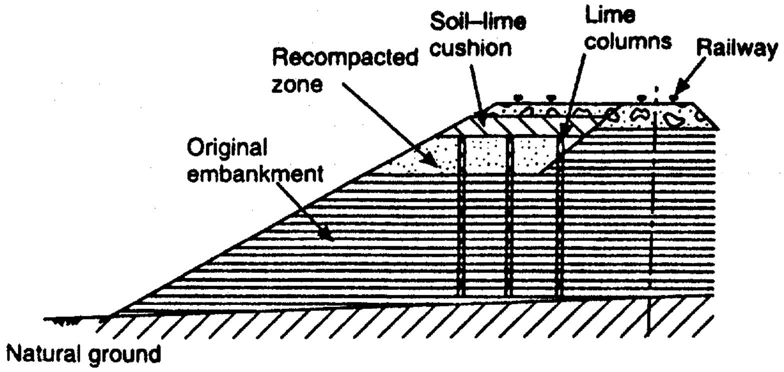


Figure 37. Cross section of a stabilized railway embankment in Bulgaria (Evstatiev et al., 1995).

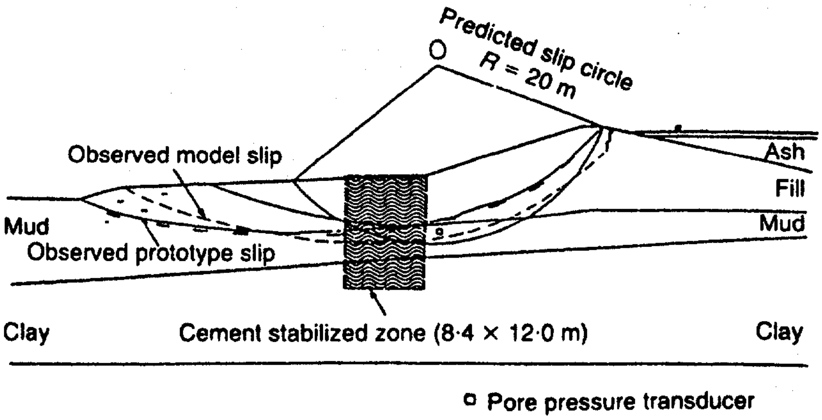


Figure 38. Coal waste embankment on soft clay in China (Xu, 1996).

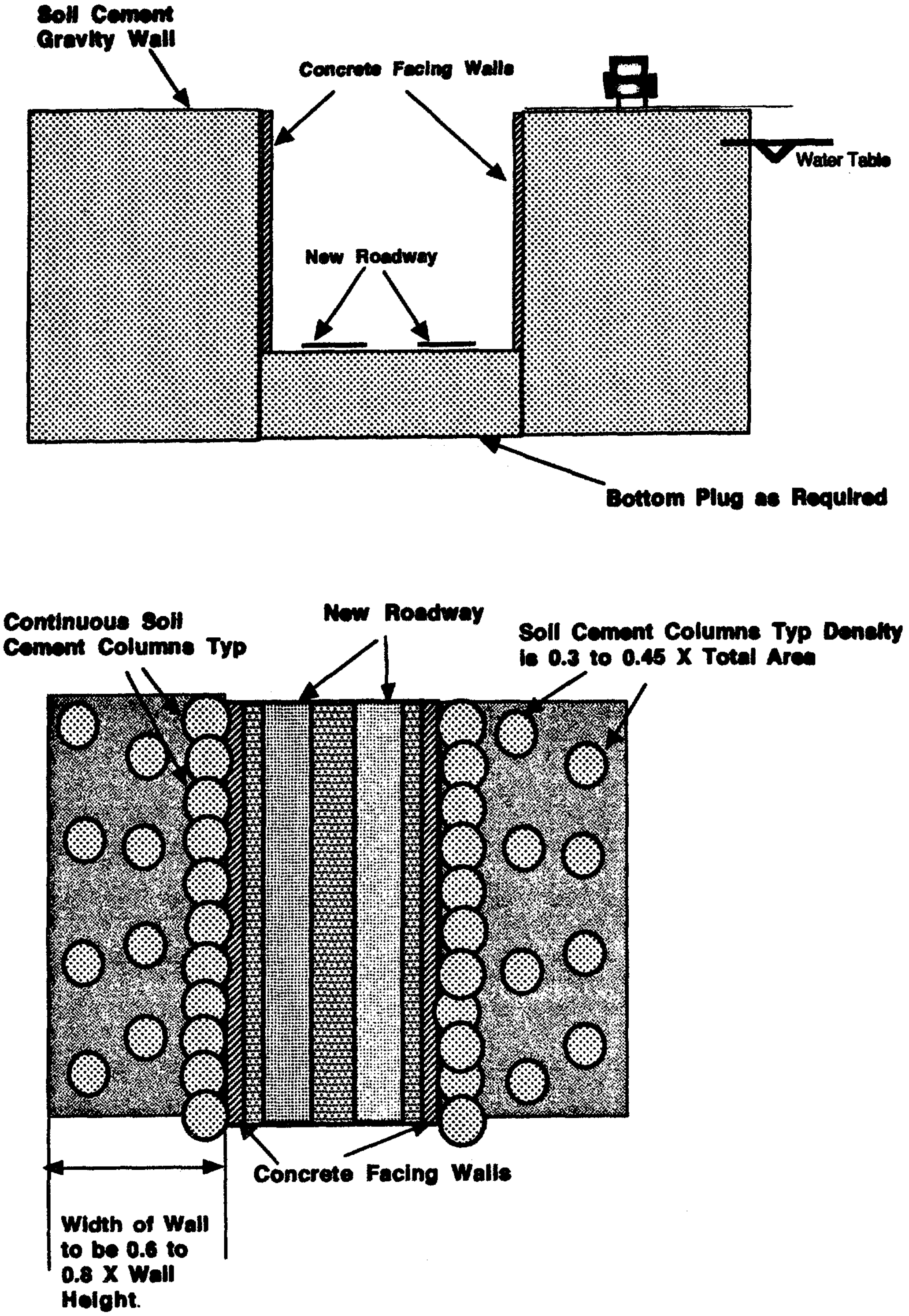


Figure 39. Cross section and plan layout of "VERTwall" (Geo-Con, Inc., 1998).

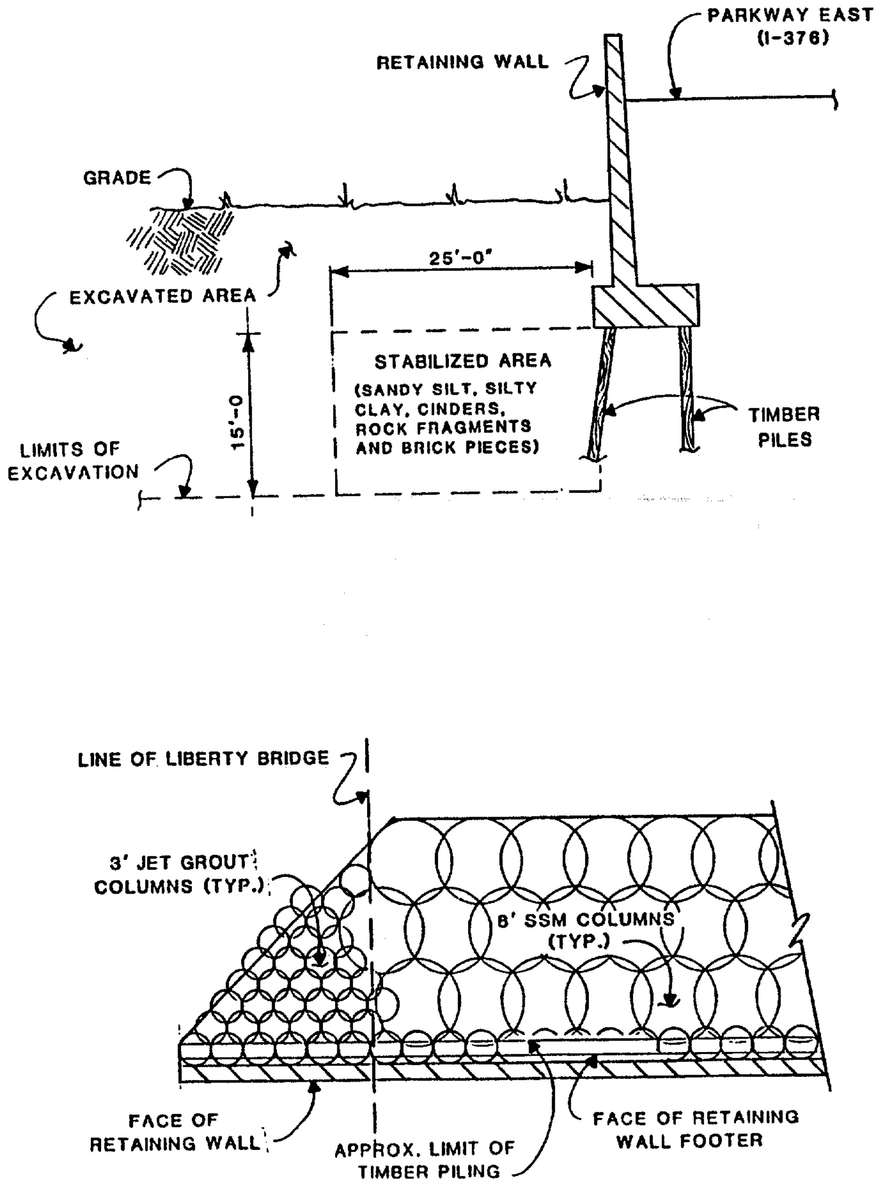


Figure 40. Layout of SSM columns and cross section of stabilized area (Walker, 1992).
(1 ft = 0.305 m)

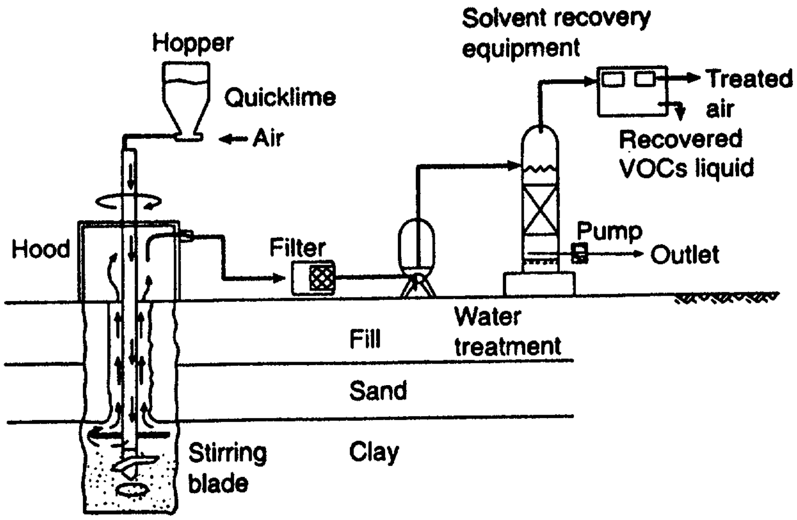
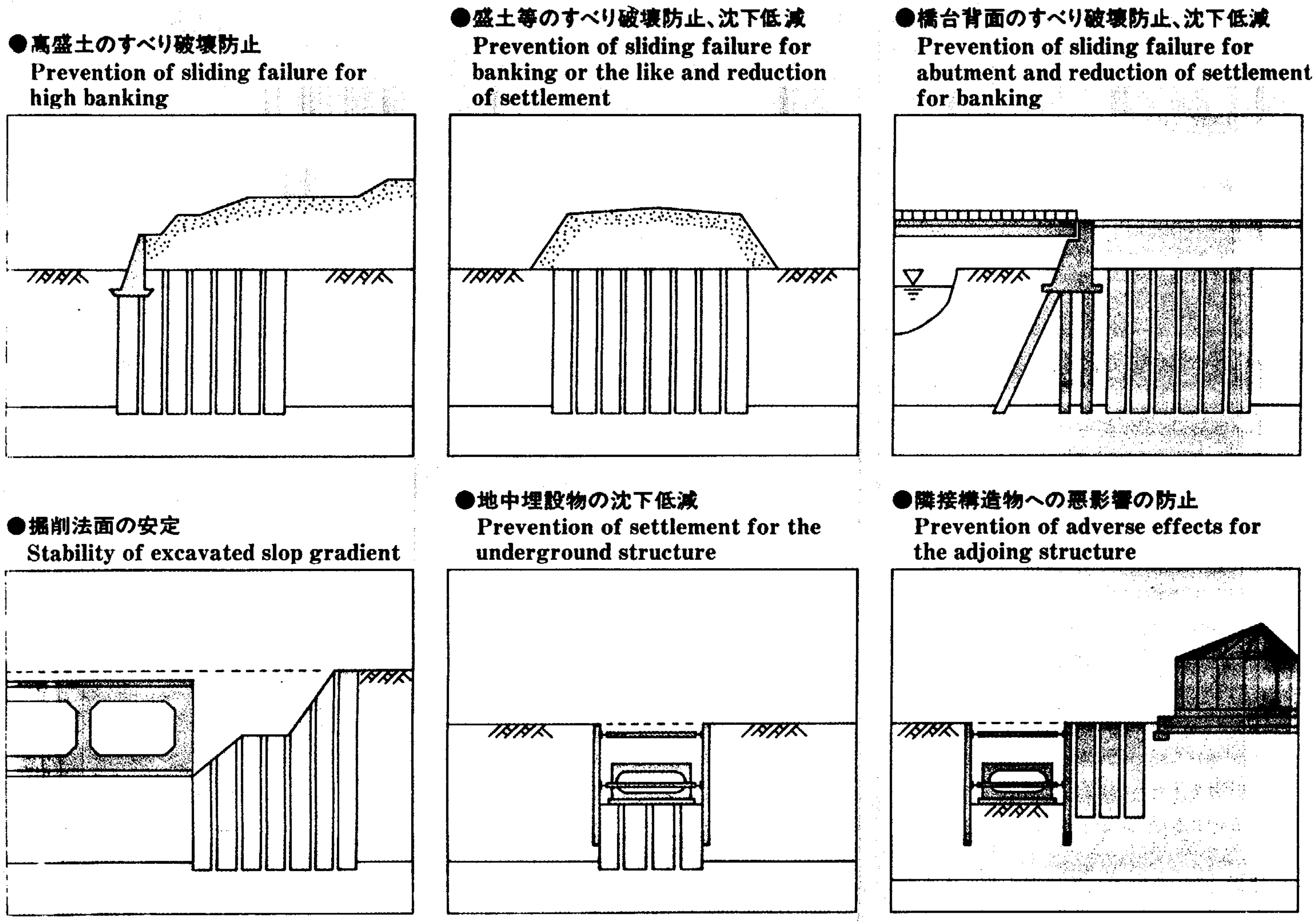


Figure 41. Remediation process for VOC removal (site location not reported) (Hidetoshi et al., 1996).



●高盛土のすべり破壊防止
Prevention of sliding failure for high banking

●盛土等のすべり破壊防止、沈下低減
Prevention of sliding failure for banking or the like and reduction of settlement

●橋台背面のすべり破壊防止、沈下低減
Prevention of sliding failure for abutment and reduction of settlement for banking

●掘削法面の安定
Stability of excavated slop gradient

●地中埋設物の沈下低減
Prevention of settlement for the underground structure

●隣接構造物への悪影響の防止
Prevention of adverse effects for the adjoing structure

Figure 42. Classification of DMM applications according to Japanese DJM Association (1996).

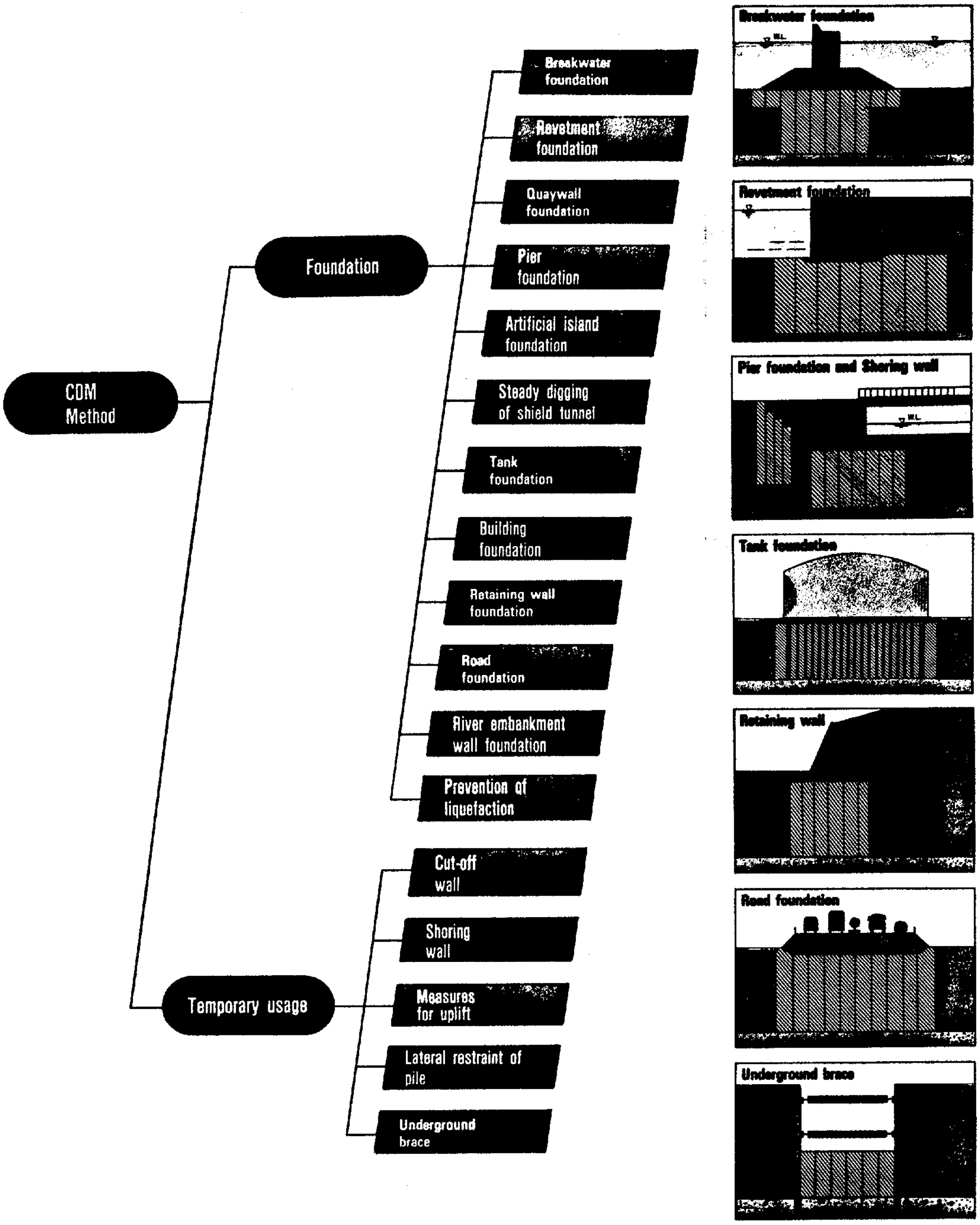


Figure 43. Classification of DMM applications according to Japanese CDM Association (1996).

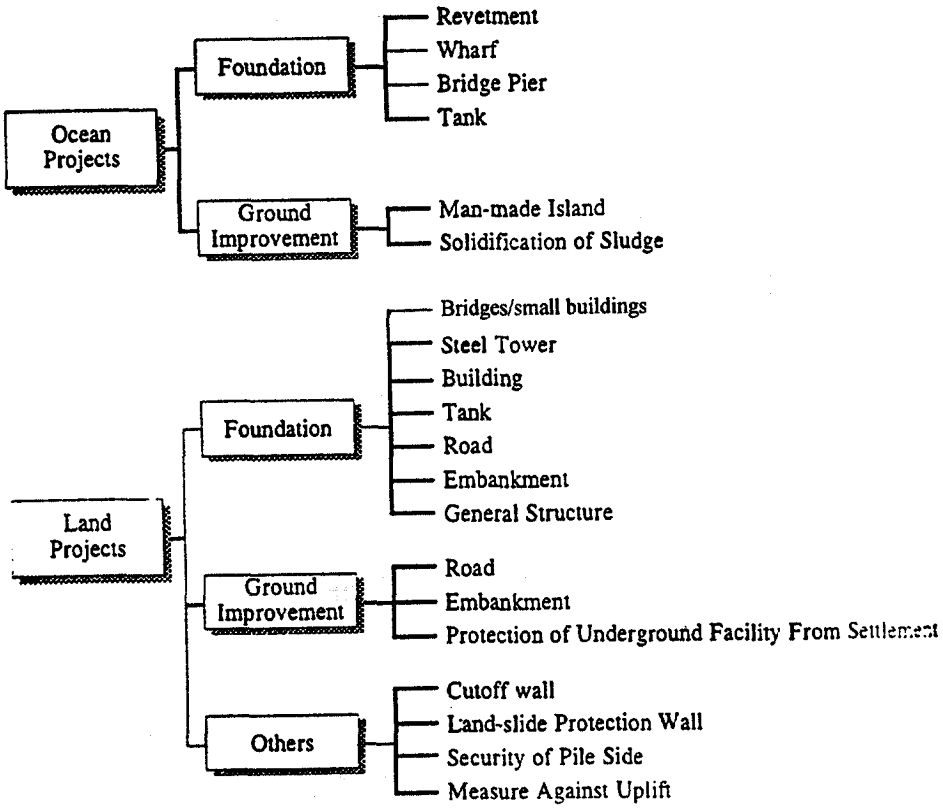


Figure 44. Proposed classification of DMM applications (FHWA, 1996).

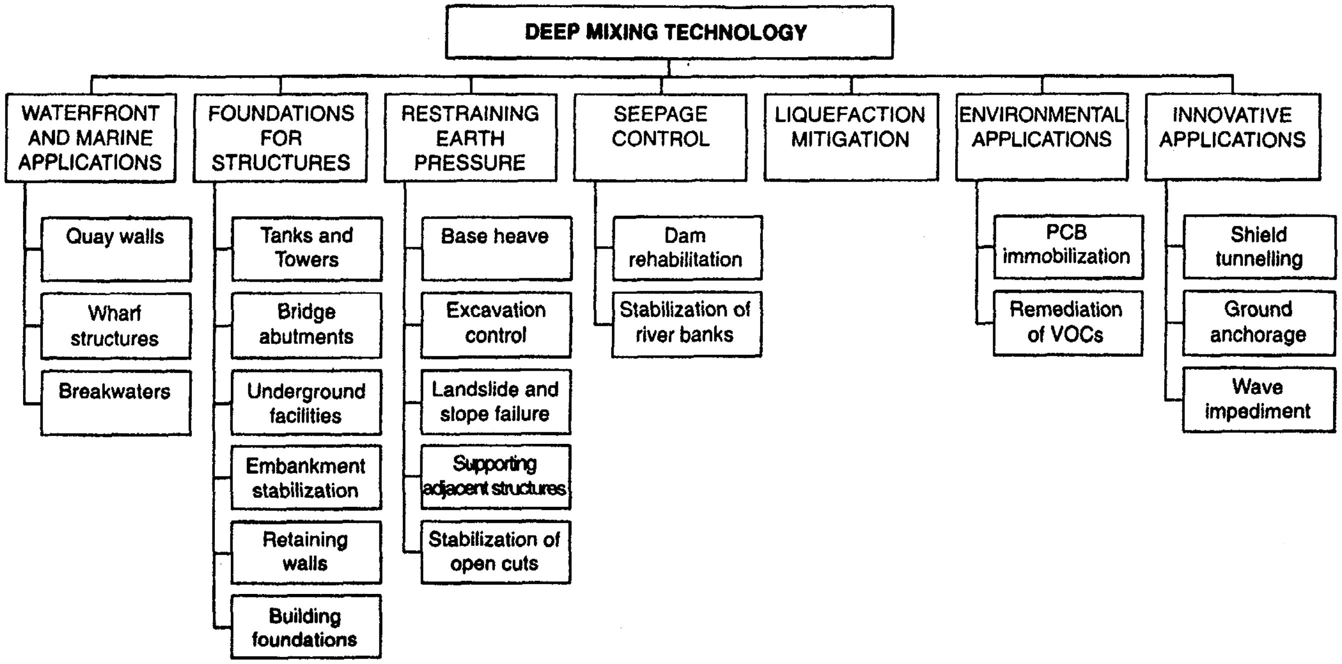


Figure 45. Proposed classification of DMM applications (Porbaha et al., 1998).

CHAPTER 4. THE APPLICATION OF DMM IN RELATION TO ALTERNATIVE COMPETITIVE TECHNOLOGIES

As illustrated in Chapter 3, DMM finds wide use in six major categories of applications internationally. On any given project, the factors leading to its use are diverse, reflecting both a number of "hard" concerns, including geotechnical, logistical, accessibility, environmental, cost, schedule, and performance factors, as well as numerous less tangible issues, including national issues, historical preferences, and the degree of influence and individual inclinations of the various contractors, consultants, and owners.

This chapter provides, Table 2, the relative advantages and disadvantages of DMM in each of the six categories. Clearly, there is a certain degree of repetition, but it is felt that this format remains the most useful for individual comparative purposes, and will permit the reader to easily add other, particular factors at will.

In examining these tables, the reader will also doubtless be aware that DMM may be regarded in certain circles still as a "new technology" and thus, on any one project, the decision on methodology may still be swayed by technological conservatism. It should also be recalled that different DMM technologies provide different types of treated soil geometries and treated soil parameters. Therefore, only one, or a few particular DMM variants may actually be practically feasible for consideration under each application. For example, lime cement columns would not be regarded as a DMM technique for Application 1 (Hydraulic Cut-Off Walls), but are very favorable for consideration in schemes relating to Application 5 (In Situ Reinforcement and Piles).

In summary, clearly, DMM is 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;
- Where treatment depths of less than about 40 m 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; 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 to be more appropriate to use alternative ground treatment technologies such as jet grouting, diaphragm walling, sheet piling, caissons, beams and lagging, driven piles, wick drains, micropiles, soil nails, vibrodensification, lightweight fills, compaction grouting, deep dynamic consolidation, bioremediation, vapor extraction, or simply to remove and replace the native soil.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications.

Application:	1. Hydraulic Cut-Offs
Competitive/ Alternative Technologies	"Diaphragm" walls (Backhoe, clamshell, or hydromill); secant piles; sheet piles; grout curtains.
Relative Advantages/Benefits of DMM	• Does not require full soil replacement, thus reducing both "binder" and spoil volumes. • Spoil can be handled as a solid waste. • Little vibration, medium-low noise (equipment can be muffled). • Can uniformly treat layered, heterogeneous soils. • Can provide good lateral continuity. • Low cost per unit area (but high mobilization cost). • In situ quality verifiable (via wet sampling, cores).
Relative Disadvantages of DMM	• Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or that may have very frequent boulders. • Can only be installed vertically. • Other methods may provide zero spoil (e.g., sheet piles). • Uniformity and quality of treated ground variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost.
General Remarks	DMM is most applicable for cut-offs in soil/fill where depths do not exceed 40 m, the soil or overhead has no obstructions, the quantity of work is large, and there is a need to minimize spoils. Good case histories exist for dams, levees, and around hazardous waste sites.

* Expanded upon in Chapter 5.

† Most methods (including all those with top-down injection) can only provide full-length treatment.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications (continued).

Application:	2. Excavation Support Walls
Competitive/ Alternative Technologies	Secant piles; sheet piles; beams and lagging; soil nailing; structural diaphragm walls.
Relative Advantages/Benefits of DMM	• Low relative cost per unit area, especially in the range of 15 to 40 m in depth. • No need for other types of lagging. • Relatively low permeability, therefore no need for additional sealing. • Spoil can be handled as a solid waste. • Little vibration, medium-low noise (equipment can be muffled). • In fluid state, allows structural elements to be introduced. • Can provide good lateral continuity. • High production in certain conditions (up to 200 m^2/shift). • Can uniformly treat layered, heterogeneous soils.
Relative Disadvantages of DMM	• Freeze/thaw degradation may occur. • Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or which may have boulders. • Can only be installed vertically. • Other methods may provide zero spoil (e.g., sheet piles). • Uniformity and quality of mixed soil variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost.
General Remarks	DMM is most applicable for construction walls through soils/fills from 15 to 40 m deep; where the soil or overhead has no obstructions; the water table is high; the quantity of work is large; steel reinforcement may be required; and the impact of noise, vibrations, and spoils must be mitigated. Good case histories exist in the U.S. of major works in Boston, Milwaukee, and the Bay Area.

* Expanded upon in Chapter 5.

† Most methods (including all those with top-down injection) can only provide full-length treatment.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications (continued).

Application:	3. Ground Treatment
Competitive/ Alternative Technologies	Permeation and jet grouting.
Relative Advantages/Benefits of DMM	• Low relative cost per unit volume to depths of 40 m. • Strength of treated soil can be engineered from 0.5 to 4 MPa. • Layout depends largely on diameter/spacing of shafts (not a design variable). • Some methods provide very low spoil volumes. • Spoil disposed of as a solid waste. • Little vibration, medium-low noise (equipment can be muffled). • Only cementitious products used. • High production capacity in certain conditions. • Quickly verifiable in situ performance via wet grab and core data. • Can be used for marine projects. • Generally good lateral and vertical levels of treatment. • Can be used in all types of soils and fills (without obstructions). • Equipment is large and complex, but execution is relatively constant and straightforward.
Relative Disadvantages of DMM	• Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or that may have boulders. • Can only be installed vertically. • Other methods may provide zero spoil. • Uniformity and quality of mixed soil variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost. • Weight of equipment may be problematic for very weak soils. • Significant variability in treated soil strength may occur, and this may be highly significant in certain applications. • Cannot be installed in close proximity to existing structures. • Less geometric flexibility of drilling and treatment.
General Remarks	DMM is most applicable for treating very large volumes of unobstructed soils and fills, either on land or underwater, where there are no overhead restrictions, and strengths of up to 4 MPa are adequate. Major case histories published on Japanese and Chinese projects, and recent work in Boston are also highly significant.

* Expanded upon in Chapter 5.

† Most methods (including all those with top-down injection) can only provide full-length treatment.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications (continued).

Application	4. Liquefaction Mitigation (via DMM cells)
Competitive/ Alternative Technologies	Vibrodensification, vibroreplacement, deep dynamic compaction, compaction grouting, dewatering drainage.
Relative Advantages/Benefits of DMM	• Excellent proven performance record in Japan. • Economical on large projects. • High production if required for emergency projects. • Minimum environmental impact. • Engineering properties of treated soil can be closely designed up to 4 MPa. • Construction quality highly verifiable (wet and dry). • Applicable in all unobstructed soil types. • Causes minimal lateral or vertical stresses that could potentially damage adjacent structures. • No recurrent post-construction expenses.
Relative Disadvantages of DMM	• Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or that may have boulders. • Can only be installed vertically. • Other methods may provide zero spoil (e.g., sheet piles). • Uniformity and quality of mixed soil variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost. • Not really applicable for remediations directly through or under existing concrete structures.
General Remarks	DMM is most applicable when used to economically and quickly create "cells" or other types of water/soil-retaining structures in large volumes in unobstructed soils or fills to depths of 40 m, without overhead obstructions, and where environmental impact must be minimized. Excellent field performance in Japan supports/supplements comprehensive laboratory and mathematical studies. First major DMM application in U.S. was for liquefaction mitigation.

* See Chapter 5

† Most methods (including all those with top-down injection) can only provide full-length treatment.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications (continued).

Application:	5. In Situ Reinforcement (Ground Improvement and Piles)
Competitive/ Alternative Technologies	Various pile types (auger cast, bored, driven, micropiles); stone columns; lightweight fills.
Relative Advantages/Benefits of DMM	• Excellent theoretical, laboratory, and field experimental data to supplement advanced design theory. • Economical for large projects in very soft, compressible soils. • New "VERT gravity wall" system does not require anchors for lateral stability. • Spacing and composition of individual columns infinitely variable. • Very fast installation potential. • Minimal environmental impact. • Some types (e.g., SCC, lime cement columns) have low mobilization costs.
Relative Disadvantages of DMM	• Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or that may have boulders. • Can only be installed vertically. • Other methods may provide zero spoil (e.g., sheet piles). • Uniformity and quality of mixed soil variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost.
General Remarks	The major application for DMM in the Nordic countries is in situ reinforcement, and this is proving increasingly attractive in other regions also. This particular application involves the whole range of DMM techniques from lime cement columns to DSM and GeoJet, but is most commonly used for improving soft, compressible soils (including those with organic material). Most case histories have been generated in Sweden; new U.S. developments are highly significant.

* See Chapter 5.

† Most methods (including all those with top-down injection) can only provide full-length treatment.

Table 2. Relative advantages and disadvantages of the use of deep mixing for each of the six general applications (continued).

Application:	6. Hazardous Waste Treatment (Fixation)
Competitive/ Alternative Technologies	Excavation/replacement; in situ treatments (vapor extraction, bio-remediation); grouting technologies; interceptor wells.
Relative Advantages/Benefits of DMM	• Treats soil in situ: multiple handling and transportation of soil and fill unnecessary. • Binder parameters variable to suit nature of hazardous materials. • Spoil controllable, and disposable as solid waste. • No post-construction expenditure necessary. • Quality of treatment verifiable during construction. • Economical for large volumes to depths of 40 m (typically less). • Individual column shapes predeterminable, thus simplifying design of layout. • Ground can be strengthened to allow for future "Brown Site" developments. • Minimal negative environmental impact.
Relative Disadvantages of DMM	• Depth limitations (40 m practical). • Need large working space for large, powerful equipment, and no overhead restrictions. • Not applicable in soils that are very dense, very stiff, or that may have boulders. • Can only be installed vertically. • Other methods may provide zero spoil (e.g., sheet piles). • Uniformity and quality of mixed soil variable in certain conditions.* • Underground utilities may pose problems. • Limited ability to treat isolated strata at depth.† • High mobilization cost.
General Remarks	DMM is seeing increasing application to fix and contain a large variety of contaminants for "closure" and redevelopment projects. It is most applicable for quickly treating large volumes of soft ground in unobstructed conditions, where spoils must be minimized. Depths to 40 m are practical, although most methods (e.g., SSM) treat to much shallower depths. Most applications to date in U.S. and Western Europe.

* See Chapter 5

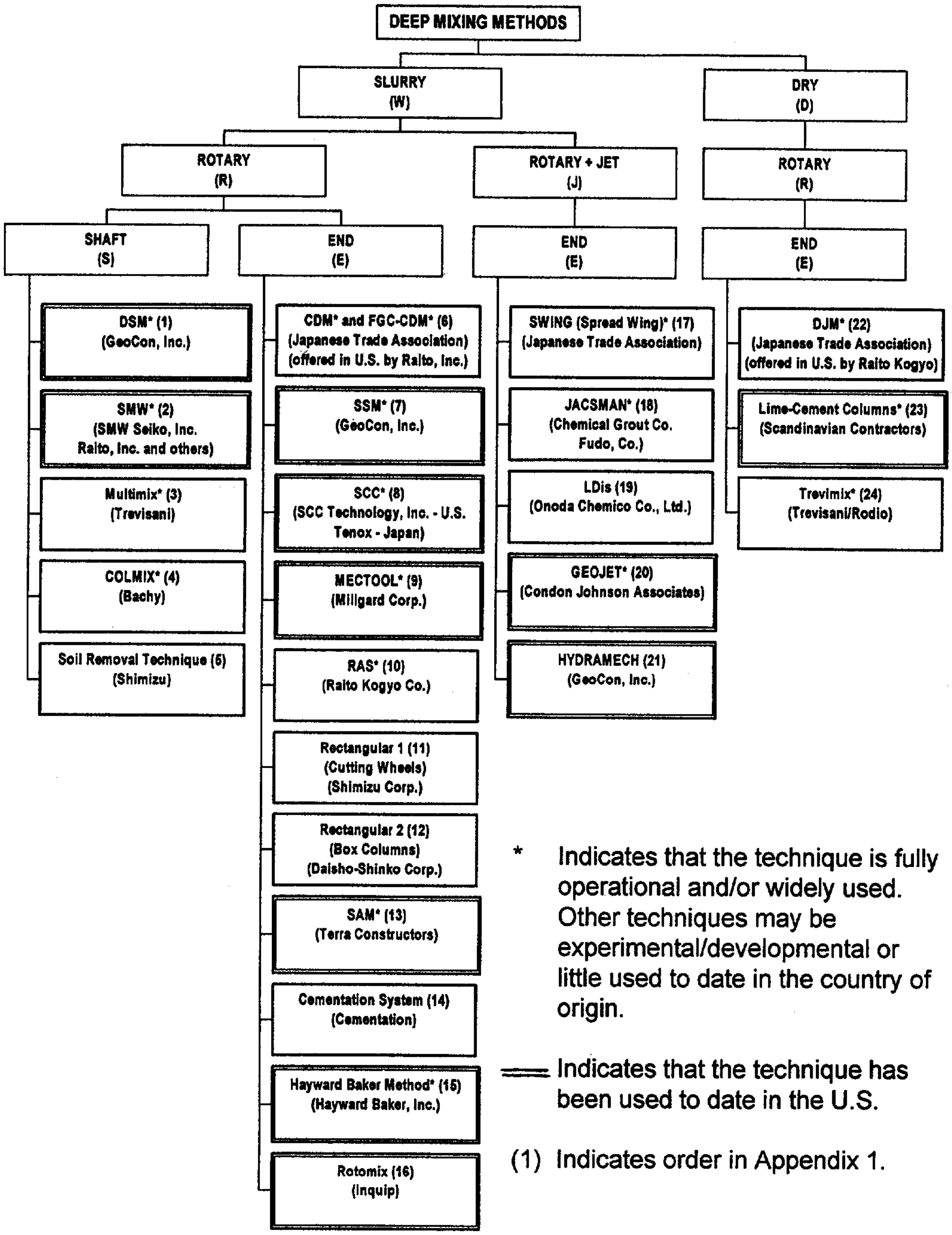
† Most methods (including all those with top-down injection) can only provide full-length treatment.

CHAPTER 5. CLASSIFICATION AND DESCRIPTION OF THE VARIOUS DEEP MIXING METHODS

As is clear from chapter 2 (Historical Development), there are many different proprietary variants of DMM. While some are at the early developmental or field demonstration stages, the majority can be regarded as fully operational within certain geographic areas and trade groupings. For example, reflecting the huge amount of treated soil projects in Japan, each of the several major "associations," such as DJM, CDM, SMW, and SWING, have numerous licensed contractors, each with many rigs of different capacities. Elsewhere, the contractors are more widely distributed, but are principally based in Scandinavia, the United States, China, and France. These markets are not yet so large in volume as in Japan, as discussed in chapter 6, and thus the contractors, or their "Deep Mixing" specialty divisions, tend to be smaller, and do not participate in the type of structured trade associations seemingly obligatory in Japan.

This report has located a total of 24 different methods described in the technical literature, and these are listed, in a newly developed classification format, in Figure 46. This classification is based on the following fundamental 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, is out of the scope of this report.)
- 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.



* Indicates that the technique is fully operational and/or widely used. Other techniques may be experimental/developmental or little used to date in the country of origin.

═ Indicates that the technique has been used to date in the U.S.

(1) Indicates order in Appendix 1.

Figure 46. Classification of Deep Mixing Methods based on "binder" (Wet/Dry); penetration/mixing principle (Rotary/Jet); and location of mixing action (Shaft/End).

To illustrate the use of the classification, 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, 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.

Each of the various DMM techniques researched during the preparation of this report is described in standard format in Appendix 1. A comparative summary is provided in Table 3. While many of the systems shown in Figure 46 are fully operational, although with a wide range of actual usage, some remain in the experimental or developmental stages. For example, the FGC-CDM system uses 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 continues in Finland (chapter 6) 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 appear to be at the full-scale field-test stage, while Rectangular 1, Soil Removal Technique, LDis, and Spread Wing have been reported to have actually been used in a full-scale project. LDis (Low Displacement Jet Column Method), like many of the newer developments, is a modified jet-grouting derivative in which mechanical means are used to reduce horizontal and vertical movements during soil treatment.

Table 3. Summary of mixing equipment and pertinent information for each technique.

Name		DSM 1	SMW 2
Classification		W-R-S	W-R-S
Company		Geo-Con, Inc.	SMW Seiko, Inc.; Raito, Inc., and others
Geography		N. America	Southeast Asia, U.S.
General Description of Most Typical Method		Multiple discontinuous augers on hanging leads rotate in alternate directions. Most of grout injected on downstroke to create panels. Neither air nor water typically used during penetration. Reverse rotation during withdrawal.	Multiple discontinuous augers on fixed leads rotate in alternate directions. Water, air or grout used on downstroke and/or grout on upstroke
Special Features / Patented Aspects		Lower 3 m usually double-stroked. Strong QA/QC by electronic methods. Patent pending on VERTWall concept.	Special electric head and gear box patented. Double-stroking "oscillation" common, especially in cohesive soils. Discontinuous auger flights and paddles are positioned at discrete intervals to reduce torque requirements. Good control over verticality feasible. Auger type varies with soil.
Details of Installation	Shafts	1-6, usually 4	2-5, usually 3
	Diameter	0.8 to 1.0 m, usually 0.9 m	0.55 to 1.5 m, usually 850-900 mm
	Realistic max. depth	45 m possible, 27 m common	60 m claimed, 35 m practical
	rpm	15-25	15-20 during penetration, depending on soil; higher during withdrawal
	Productivity/ output	0.6-1.0 m/min penetration (slower in clays and dense sands); 2 m/min withdrawal/mixing; 100-150 m^2/shift industrial	0.5-1.5 m/min penetration; 1.5-2 m/min withdrawal/mixing; 100-200 m^3 per shift, i.e., 100-150 m^2 per shift
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout ± bentonite ± clay and other materials and additives, such as ash, slag	Cement grout ± bentonite and other additives such as ash, slag
	w/c ratio	1.2-1.75 (typically 1.5 on penetration and 1 to 1.25 during withdrawal)	1.25-1.50 (sands) - 2.5 (cohesives)
	Cement factor (kg_{cement}/m^3_{soil})	120-400 kg/m^3	200-750 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	15-40%	50-100%
Reported Treated Soil Properties	U.C.S.	0.3-7 MPa (clay strengths approx. 40% of those in sands); In sands, 2+ MPa	0.3-1.3 MPa (clays) 1.2-4.2 MPa (sands)
	k	1×10^{-7} to 1×10^{-9} m/s	1×10^{-7} to 1×10^{-10} m/s
	E	300 to 1000 x U.C.S.	350 to 1350 x U.C.S.
Specific Relative Advantages and Disadvantages		Economical, proven systems; mixing efficiency can be poor in stiff cohesive soils (especially SMW Seiko); can generate large spoil volumes, proportional to volume ratio required for mixing efficiency and treated soil requirements	
Notes		First DSM application at Bay City, MI in 1987.	Developed by Seiko in 1972: first used 1976 in Japan, 1986 in U.S. Trade Association in Japan.
Representative References		Ryan and Jasperse (1989, 1992); Day and Ryan (1995); Nicholson et al., 1998	Taki and Yang (1989, 1991); Yang (1997)

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Multimix (Trevimix) 3	Colmix 4
Classification		W-R-S	W-R-S
Company		Trevisani	Bachy
Geography		Italy, U.S.	Europe
General Description of Most Typical Method		Multiple cable-suspended augers rotate in opposite directions. Grout injected during penetration. Prestroked with water in clays. Auger rotation reversed during withdrawal. Mixing occurs over 8- to 10-m length of shaft.	Counter-rotating mixing shafts from fixed leads penetrate ground while slurry is injected. Blended soil moves from bottom to top of hole during penetration, and reverses on withdrawal. Restroking of columns in cohesive soils.
Special Features / Patented Aspects		Pre-drilling with water ± additives in very resistant soils. Process is patented by TREVI. Developed especially for cohesionless soils of low/medium density, and weak clays.	6 to 8 auger machines noted in Australian patent (1995). Changing direction of augers during extraction compacts columns. Patented in U.S. 4,662,792 (1987). Automatic drilling parameter recorder synchronizes rate of slurry injection with penetration rate.
Details of Installation	Shafts	1-3, typically 3. Configuration varies with soil.	2, 3, or 4 common (6-8 possible)
	Diameter	0.55-0.8 m at 0.4 to 0.6-m spacings	0.23 to 0.85 m
	Realistic max. depth	25m	20 m (10 m common)
	rpm	12-30	NA*
	Productivity/ output	0.35-1.1 m/min penetration (typically 0.5) 0.48-2 m/min withdrawal	0.8 m/min penetration; 1.0 m/min withdrawal; 200-300 m/shift
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout mainly, plus bentonite in sands; additives common, even in predrilling phase	Cement, lime, flyash, and special grouts to absorb heavy metals and organics
	w/c ratio	Typically low, i.e., 0.6-1.0 (especially in cohesives)	1.0 typical, but wide range
	Cement factor (kg$_{cement}$/m^3$_{soil}$)	200-250 kg/m^3 typical (80-450 kg/m^3 range)	Up to 320 kg/m^3 (200 kg/m^3 typical)
	Volume ratio (Vol$_{grout}$:Vol$_{soil}$)	15-40%	30-50%
Reported Treated Soil Properties	U.C.S.	0.5-5 MPa (sands); 0.2-1 MPa (silts, clays); up to 20 MPa in very hard soils	3-4 MPa (clay), higher for sands
	k	< 1 x 10^{-8} m/s	< 1 x 10^{-7} m/s
	E	ND*	50 to 100 x U.C.S.
Specific Relative Advantages and Disadvantages		Goals are to minimize spoils (10-20%) and presence of unmixed zones within and between panels	Low spoil claimed. Can be used on slopes and adjacent to structures. Columns have 10-20% larger diameters than shafts due to compaction effect. Flexible equipment and mix design.
Notes		Developed jointly in 1991 by TREVI and Rodio.	Developed in France in late 1980s.
Representative References		Pagliacci and Pagotto (1994)	Harnan and Iagolnitzer, 1992

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Soil Removal Technique 5	CDM 6
Classification		W-R-S	W-R-E
Company		Shimizu Corporation	More than 48 members of CDM Association in Japan
Geography		Japan	Japan, China
General Description of Most Typical Method		Upper continuous auger flights on fixed leads extract soil to ground surface during penetration. Lower mixing blades rotate and mix soil with injected slurry during withdrawal.	Fixed leads support shafts with 4-6 mixing blades above drill bit. Grout injected during penetration and (mainly) withdrawal. Also a 2- to 8-min mixing period at full depth.
Special Features / Patented Aspects		Continuous flight augers from drill tip to the ground surface remove soil to limit ground displacements and lateral stresses during mixing.	Comprises numerous subtly different methods all under CDM Association
Details of Installation	Shafts	2	2-8 (marine): 1-2 (land) (each with 4-6 blades) (12 have been used)
	Diameter	1-1.2 m	1-2 m (marine): 0.7-1.5 m (land)
	Realistic max. depth	40 m	70 m (marine): 40 m (land)
	rpm	ND*	20-30 (penetration); 40-60 (withdrawal)
	Productivity/ output	ND*	0.5-2 m/min (avg. 1 m/min) (penetration) 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	Cement grout*	Wide range of materials, including portland or slag cement, bentonite, gypsum, flyash, using fresh or seawater; plus various additives.
	w/c ratio	ND*	0.6-1.3, typically 1.0
	Cement factor (kg_{cement}/m^3_{soil})	ND*	100-300 kg/m^3, typically 140 to 200 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	ND*	20-30%
Reported Treated Soil Properties	U.C.S.	0.5 MPa (in soft silt) (70% of conventional DMM)	Strengths can be closely controlled, by varying grout composition, from < 0.5-4 MPa (typically 2-4)
	k	ND*	1×10^{-8} to 1×10^{-9} m/s
	E	ND*	350 to 1000 x U.C.S. (lab) 150 to 500 x U.C.S. (field)
Specific Relative Advantages and Disadvantages		Reduces horizontal displacements and stresses imposed during mixing. Obviates need for pre-augering.	Vast amount of R&D information available. Specifically developed for softer marine deposits and fills, now also used for land-based projects.
Notes		Operational prototype stage. Possibly patented. *Assumed similar to CDM.	Association founded in 1977. Research initiated under Japanese Government (1967). Offered in the U.S. by Raito, Inc.
Representative References		Hirai et al., 1996	CDM (1996); Okumura (1996)

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		SSM 7	SCC 8
Classification		W-R-E	W-R-E
Company		Geo-Con, Inc.	SCC Technology, Inc.
Geography		U.S.	SCC (U.S.); Tenox (Japan)
General Description of Most Typical Method		Single large-diameter auger on hanging leads or fixed rotary table is rotated by bottom rotary table and slurry or dry binder is injected. Auger rotation and injection continue to bottom of treated zone. Auger rotation during withdrawal usually without injection.	Grout is injected from shafts on fixed leads during penetration. A "share blade" is located above tip (non-rotating). At target depth, 1 minute of additional injection plus oscillation for 1.5-3 m. Withdrawal with counter rotation and no further grout injection.
Special Features / Patented Aspects		Single large-diameter auger; cycling up and down is common to improve mixing efficiency.	Very thorough mixing via "share blade" action, which is patented.
Details of Installation	Shafts	1	Single with 3 pairs of rotated mixing blades plus "share blade". Double shafts are possible for ground stabilization; single shaft for piles.
	Diameter	1-4 m	0.6-1.5 m; 1.2 m for double shafts.
	Realistic max. depth	12 m	20 m max
	rpm	15	30-60
	Productivity/ output	500-1500 m^3 per shift	1 m/min penetration and withdrawal 100 m^2 of wall up to 400 m of piles/8-h shift
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout, bentonite, flyash, lime, and other additives for contaminant immobilization	Typically cement grout, but others, e.g., ash, bentonite, possible.
	w/c ratio	1-1.75	0.6-0.8 (clays) to 1.0-1.2 (sands)
	Cement factor (kg_{cement}/m^3_{soil})	200-400 kg/m^3	150-400 kg/m^3 cement
	Volume ratio (Vol_{grout}:Vol_{soil})	12-20%	25-35%
Reported Treated Soil Properties	U.C.S.	3.5-10 MPa in granular soils. 0.6-1.2 MPa common in high-water-content sludges.	3.5-7 MPa (sands) 1.3-7 MPa (cohesives)
	k	1 x 10^{-10} m/s possible.	1 x 10^{-8} m/s
	E	100 to 300 x U.C.S.	180 x U.C.S.
Specific Relative Advantages and Disadvantages		Can treat wide variety of contaminants, including creosote, tar, organics, petroleum, etc.	Low spoil with minimal grout loss claimed, due to low w/c and minimized injected volume. Very efficient mixing.
Notes		Mainly used for environmental applications to date, but increasing use in geotechnical field	Used since 1979 in Japan and 1993 in U.S.
Representative References		Walker, 1992; Day and Ryan, 1995; Nicholson et al., 1997	Taki and Bell (1997)

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		MecTool® 9	RAS Column Method 10
Classification		W-R-E	W-R-E
Company		Millgard Corporation	Raito Kogyo, Co.
Geography		U.S. and U.K.	Japan
General Description of Most Typical Method		For cohesive soils, grout is placed in pre-drilled hole in center of each element, and soil in the annulus of the tool is then blended with mixing tool. End mixing with grout injected through hollow kelly bar.	Large diameter, single-shaft, concentric double-rod system on fixed lead is rotated at high rpm into ground, and grout injected over zone to be treated. Unit cycled up and down through zone with or without additional grout injection.
Special Features / Patented Aspects		MecTool (U.S. Patent #5,135,058). Also Aqua MecTool (U.S. Patent #5,127,765), describes an isolation mechanism that encloses submerged mixing tool in remediation zone providing protection against secondary contamination	Cutting blade on inner rod rotates in opposite direction from two mixing blades on outer rod. Slurry injection ports located at base of inner rod.
Details of Installation	Shafts	1	1
	Diameter	1.2-4.2 m max.	1.4 and 2.0 m (larger than typical CDM)
	Realistic max. depth	25 m max (typically less than 6m)	24 m typical; 28 m possible.
	rpm	ND*	Up to 40 (in each direction)
	Productivity/ output	0.6 m/min	0.5 m/min penetration 1 m/min withdrawal
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grouts including PFA and other materials ± proprietary additive to breakdown "plastic seals thereby enabling through-the-tool delivery"	Cement grout
	w/c ratio	ND*	0.8 (field trial)
	Cement factor (kg_{cement}/m^3_{soil})	ND*	300 kg/m^3 (field trial)
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	20-35% estimated range	33% (field trial)
Reported Treated Soil Properties	U.C.S.	0.8-2.5 MPa	1-6 MPa
	k	1 x 10^{-8} to 1 x 10^{-9} m/s	ND*
	E	ND*	ND*
Specific Relative Advantages and Disadvantages		"Excellent control of grout and spoil quantity"	Large-diameter auger speeds production, computer control and monitoring, uniform mixing. Specially useful in dense soils.
Notes		Mainly environmental applications to date.*Probably similar to SSM	*Assumed similar to CDM
Representative References		Millgard Corporation, 1993	Isobe et al., 1996

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Rectangular 1 (Cutting Wheels) 11	Rectangular 2 (Box Columns) 12
Classification		W-R-E	W-R-E
Company		Shimizu	Daisho Shinko Corp.
Geography		Japan	Japan
General Description of Most Typical Method		A pair of laterally connected shafts with horizontal mixing blades and vertical vanes are rotated during penetration. Grout injection during penetration and/or withdrawal. Vertical vanes create rectangular elements.	Mixing shaft rotated, "box casing" conveyed (without rotation), and grout injected during penetration. Shaft is counter-rotated during withdrawal.
Special Features / Patented Aspects		Use of claw-like vanes to create rectangular columns; vanes may be patented. Inclinometer fixed to mixing unit to monitor verticality.	Use of box casing, which surrounds mixing tools and contains treated soil to create square or rectangular columns.
Details of Installation	Shafts	2	1 with 4 horizontal mixing blades
	Diameter	1-m x 1.8-m columns	1-m square box
	Realistic max. depth	15 m	ND*
	rpm	ND*	30 (shaft only)
	Productivity/ output	1 m/min penetration/withdrawal	0.5 m/min penetration 1 m/min withdrawal
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout	Cement grout
	w/c ratio	ND*	1.0-1.2
	Cement factor $(kg_{cement}/m^3{}_{soil})$	ND*	150-400 kg/m^3
	Volume ratio $(Vol_{grout}:Vol_{soil})$	ND*	ND*
Reported Treated Soil Properties	U.C.S.	ND*	1.2-4.2 MPa
	k	ND*	ND*
	E	ND*	ND*
Specific Relative Advantages and Disadvantages		Rectangular columns require less overlap than circular. Vertical flow during mixing, larger cross-sectional column area per stroke.	Square/rectangular columns require less overlapping than circular columns. Uniform mixing promoted.
Notes		Operational prototype stage. *Assumed similar to CDM	Operational prototype stage.*Assumed similar to CDM.
Representative References		Watanabe et al., 1996	Mizutani et al., 1996

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Single Auger Mixing (SAM) 13	Cementation 14
Classification		W-R-E	W-R-E
Company		Terra Constructors	Kvaerner Cementation
Geography		U.S.	U.K.
General Description of Most Typical Method		Large-diameter mixing tool on hanging leads rotated, with slurry injection during penetration.	Single auger on fixed leads rotated during penetration. Auger cycled up and down through 1-m length five times, then raised to next 1-m increment. Repeat to surface. Injection upon penetration, cycling, and/or withdrawal
Special Features / Patented Aspects		Multiple-auger mixing capability (MAM) foreseen for deeper applications.	Combination of a short interrupted length of auger with smaller diameter continuous flights.
Details of Installation	Shafts	1	1
	Diameter	1-3.6 m	0.75 m (1 m also possible)
	Realistic max. depth	13 m max.	10+ m
	rpm	8-16	ND*
	Productivity/ output	380 m^3/8-h shift	0.5-0.67 m/min penetration/mixing
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout mainly, and other additives for oxidation/stabilization of contaminants.	Cement grout with or without flyash
	w/c ratio	0.75-1.0	0.4
	Cement factor (kg_{cement}/m^3_{soil})	ND*	60-130 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	10-20% by weight	Unknown
Reported Treated Soil Properties	U.C.S.	Varies dependent upon soil type; up to 3.5 MPa	5-10 MPa
	k	Similar to in situ soil	ND*
	E	ND*	ND*
Specific Relative Advantages and Disadvantages		Applicable in soils below water table. Environmental applications.	Low spoil, low heave potential, specific horizons can be treated, good in saturated ground where dewatering cannot be used.
Notes		Developed since 1995.	Not now apparently used in U.K. due to market conditions.
Representative References		Terra Constructors, 1998	Greenwood, 1987

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		HBM (Single Axis Tooling) 15	Rotomix 16
Classification		W-R-E	W-R-E
Company		Hayward Baker Inc., a Keller Co.	INQUIP Associates
Geography		U.S. (but with opportunities for sister companies worldwide)	U.S. and Canada
General Description of Most Typical Method		Cable-suspended shaft rotated by bottom rotary drive table. Grout injected usually during penetration, followed by 5 minutes mixing and oscillation at full depth, and rapid extraction with injection of "backfill grout" only (1-5% total).	Single rotating shaft and bit; Grout injection
Special Features / Patented Aspects		Method proprietary to Keller.	Proprietary to INQUIP
Details of Installation	Shafts	Single with 2 or 3 pairs of mixing paddles above drill bit.	Single, rotating bit with paddles
	Diameter	0.5-3.5 m, typically 2.1 and 2.4 m	1.2 to 4.8 m
	Realistic max. depth	20 m max.	3-30 m (depends on auger diameter)
	rpm	20-25 (penetration); higher upon withdrawal	5-45
	Productivity/ output	0.3-0.5 m/min (penetration); faster upon withdrawal. In excess of 500 m^3/shift	ND*
Mix Design *(depends on soil type and strength requirements)*	Materials	Varied in response to soil type and needs	Cement
	w/c ratio	1-2 (typically at lower end)	0.8-2 typical
	Cement factor (kg_{cement}/m^3_{soil})	150 kg/m^3	>100 kg/m^3
	Volume ratio $(Vol_{grout}:Vol_{soil})$	15-30%	>15%
Reported Treated Soil Properties	U.C.S.	3.5-10 MPa (sands) 0.2-1.4 MPa (clays)	>0.1 MPa
	k	1×10^{-10} m/s possible	$< 1 \times 10^{-8}$ m/s typical
	E	ND*	ND*
Specific Relative Advantages and Disadvantages		Good mixing; moderate penetration capability; low spoils volume. Dry binder method also available.	Good penetration/mixing. Dry binder available for use in treating sludges.
Notes		In development since 1990. Commercially viable since 1997.	Developed in 1990, mainly used for environmental applications. Limited data.
Representative References		Burke et al., 1998	INQUIP Associates, 1998.

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Spread Wing (SWING) 17	JACSMAN 18
Classification		W-J-E	W-J-E
Company		Taisei Corporation/Raito Kogyo, Co. & others	Chemical Grout Co., Fudo Co., & others
Geography		Japan, U.S.	Japan
General Description of Most Typical Method		With blade retracted, 0.6-m diameter pilot hole is rotary drilled to bottom of zone to be treated. Blade expanded and zone is treated with rotary mixing to 2-m diameter and air jetting to 3.6 m diameter.	Twin counter-rotating shafts, grout injected at low pressure from cutting blades during penetration. During withdrawal, inclined, crossed jets on upper two pairs of blades are used at high velocities to increase diameter and enhance mixing efficiency
Special Features / Patented Aspects		Retractable mixing blade allows treatment of specific depths to large diameter. Concentric mechanically mixed and jet mixed zones are produced. Patented. Trade association.	The combination of DMM and jet grouting ensures good joints between adjacent columns, and columns of controlled diameter and quality. Column formed is nominally 1.9 m x 2.7 m in plan. Patented process. Trade association.
Details of Installation	Shafts	1	2 shafts at 0.8-m spacing each with 3 blades.
	Diameter	0.6-m pilot hole, 2.0-m (mechanical) to 3.6-m (jetted) column	1 m (blades at 0.8-m spacing along shaft)
	Realistic max. depth	40 m	20 m
	rpm	ND*	20
	Productivity/ output	0.03-0.1m/min penetration	1 m/min penetration 0.5-1 m/min withdrawal
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout	Cement grout
	w/c ratio	ND*	1.0
	Cement factor $(kg_{cement}/m^3{}_{soil})$	450 kg/m^3	200 kg/m^3 (jetted); 320 kg/m^3 (DMM). Air also used to enhance jetting
	Volume ratio $(Vol_{grout}:Vol_{soil})$	ND*	200 L/min per shaft during DM penetration; 300 L/min per shaft during withdrawal (jetting); i.e., 20-30%
Reported Treated Soil Properties	U.C.S.	0.4-4.4 MPa (mechanically mixed zone); 1.5 MPa (sandy), 1.2 MPa (cohesive) (jet-mixed zone)	2-5.8 MPa (silty sand and clay) 1.2-3 MPa (silty sand)
	k	1 x 10^{-8} m/s	ND*
	E	150 x U.C.S. (mechanically mixed zone); 100 x U.C.S. (jet-mixed zone)	ND*
Specific Relative Advantages and Disadvantages		Variable column size generated by varying pressures; retractable/expandable blade, jet mixing allows good contact with adjacent underground structures in difficult access areas.	New system combining DMM and jet-grouting principles to enhance volume and quality of treatment; jetting provides good overlap between columns.
Notes		SWING Association with 17 members established in late 1980s in Japan.	Name is an acronym for Jet and Churning System Management.
Representative References		Kawasaki, 1996; Yang et al., 1998	Miyoshi and Hirayama (1996)

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		LDis 19	GeoJet 20
Classification		W-J-E	W-J-E
Company		Onoda Chemical Co., Ltd.	Condon Johnson and Associates
Geography		Japan	Western U.S.
General Description of Most Typical Method		The mixing tool is rotated to full depth. Tool is withdrawn (rotating) to break up and remove the soil, followed by re-penetration to full depth. Grout is injected during second withdrawal via jets, at high pressure.	Grout is jetted via ports on a "processor" during rapid penetration. The wings cut the soil and the jetted grout blends it.
Special Features / Patented Aspects		Conventional jet grout equipment with addition of single-blade auger to reduce volume of material displaced by jet and, therefore, limit ground movement (i.e., make volume injected equal to volume removed).	Combination of mechanical and hydraulic cutting/mixing gives high-quality mixing and fast penetration. Licensed by CJA for five western states. Trevi-ICOS for the remainder. Very low environmental impact.
Details of Installation	Shafts	1	1 shaft with pair of wings or similar "processor"
	Diameter	About 1.0 m (jetted)	0.6-1.2 m
	Realistic max. depth	20 m	45 m max (25 m typical)
	rpm	3-40	150-200 (recent developments focusing on 80-90 rpm)
	Productivity/ output	0.33 m/min penetration. Overall, about 65% that of jet grouting.	2-12 m/min (penetration) (6 m/min typical) 15 m/min (withdrawal); 150 m of piles/h possible
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement grout*	Cement grout; additives if necessary
	w/c ratio	ND*	0.5-1.5 (typically 0.8-1.0)
	Cement factor (kg_{cement}/m^3_{soil})	ND*	150-300 kg/m^3
	Volume ratio ($Vol_{grout}:Vol_{soil}$)	About 40%	20-40%
Reported Treated Soil Properties	U.C.S.	2 MPa	0.7-5.5 MPa (Bay mud) 4.8-10.3 MPa (Beaumont clay)
	k	ND*	ND*
	E	ND*	ND*
Specific Relative Advantages and Disadvantages		Re-penetration causes production to be low. Spoil volume approximately equal to injected volume. Minimal ground heave.	Computer control of penetration parameters excellent. High strength. Low spoil volumes. High repeatability. Excellent mixing. High productivity.
Notes		Operational prototype stage. *Assumed similar to conventional jet grouting.	Developed since early 1990s. Fully operational in Bay Area. Five patents on "processor", system, and computer control; three patents pending.
Representative References		Ueki et al., 1996	Reavis and Freyaldenhoven (1994)

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Hydramech 21	Dry Jet Mixing 22
Classification		W-J-E	D-R-E
Company		Geo-Con, Inc.	DJM Association (64 companies)
Geography		U.S.	Japan
General Description of Most Typical Method		Drill with water/benonite or other drill fluid to bottom of hole. No compressed air used. At bottom, start low-pressure mechanical mixing through shaft. Cycle three times through bottom zone. Multiple high-pressure jets started at same time (350-450 MPa).	Shafts are rotated while injecting compressed air from the lower blades to avoid clogging of jet nozzles. Dry materials are injected during withdrawal via compressed air, and with reverse rotation. Air vents to surface around the square section shafts.
Special Features / Patented Aspects		2-mm-diameter "hydra" nozzles on outer edges of mixing tool. Mechanical mixing occurs in center of columns, chunks of soil forced to perimeter where disaggregation occurs by jets.	System is patented and protected by DJM Association. Two basic patents (blade design and electronic control system). Many supplementary patents.
Details of Installation	Shafts	1	1-2 shafts adjustably spaced at 0.8 to ~1.5 m, each with 2-3 pairs of blades
	Diameter	1.2-m paddles on 0.9-m auger; column up to 2-m diameter, depending on jet effectiveness.	1 m
	Realistic max. depth	20+ m	33 m max.
	rpm	10-20	24-32 during penetration. Twice as high during withdrawal.
	Productivity/ output	Up to 500 m^3/shift	0.5 m/min penetration; 3 m/min withdrawal.35-45% lower in low-headroom conditions
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement	Usually cement, but quicklime is used in clays of very high moisture content
	w/c ratio	1.0-1.5	NA*
	Cement factor $(\text{kg}_{\text{cement}}/\text{m}^3{}_{\text{soil}})$	100-250 kg/m^3	100-400 kg/m^3 (sands and fine grained soil using cement); 200-600 kg/m^3 (peats and organics using cement); 50-300 kg/m^3 (soft marine clays using lime)
	Volume ratio $(\text{Vol}_{\text{grout}}:\text{Vol}_{\text{soil}})$	10-15% by weight of soil.	NA*
Reported Treated Soil Properties	U.C.S.	Up to 10 MPa	Greatly varies depending on soil and binder, 1-10 MPa
	k	Up to 1 x 10^{-9} m/s	"Higher than CDM permeabilities"
	E	100 to 300 x U.C.S.	E_{50} = 50 to 200 x U.C.S.
Specific Relative Advantages and Disadvantages		No air used. Very uniform mixing. Control over diameters provided at any depth. Several times cheaper than jet grouting. Mixing can be performed within specific horizons, i.e., plugs can be formed instead of full columns.	Heavy rotary heads remain at bottom of leads, improving mechanical stability of rigs, especially in soft conditions. Very little spoils; efficient mixing. Extensive R&D experience. Fast production on large jobs.
Notes		Field-tested at Texas A&M. Fully operational from 1998.	Sponsored by Japanese Government and fully operational in 1980. (First application in 1981.) Offered in the U.S. by Raito, Inc. since 1998.
Representative References		Geo-Con, Inc., 1998	DJM Brochure (1996); Fujita (1996); Yang et al., 1998

*ND = No data; NA = Not applicable.

Table 3. Summary of mixing equipment and pertinent information for each technique (continued).

Name		Lime Cement Columns 23	Trevimix 24
Classification		D-R-E	D-R-E
Company		Various (in Scandinavia/Far East). Stabilator alone in U.S.	TREVI, Italy
Geography		Scandinavia, Far East, U.S.	Italy, Eastern U.S., Far East
General Description of Most Typical Method		Shaft is rotated while injecting compressed air below mixing tool to keep injection ports clear. Dry materials are injected during withdrawal via compressed air, and reverse rotation. Requires sufficient free water to hydrate binder, e.g., sand >15%; silt >20%; clay >35%.	Soil structure disintegrated during penetration with air. Augers are then counter-rotated on withdrawal and dry materials are injected via compressed air through nozzles on shaft below mixing paddles. Binder can also be added during penetration.
Special Features / Patented Aspects		Very low spoil. High productivity. Efficient mixing. No patents believed current. Strong reliance on computer control. Close involvement by SGI.	Use of "protection bell" at surface to minimize loss of vented dry binder. System is patented by Trevi and also used under license by Rodio. Needs soil with moisture content of 60-145+%, given relatively high cement factor and diameter.
Details of Installation	Shafts	Single shaft, various types of cutting/mixing blades.	1-2 (more common). Separated by fixed (but variable) distance of 1.5-3.5 m.
	Diameter	0.5-1.2 m, typically 0.6 or 0.8 m	0.8-1.0 m (most common)
	Realistic max. depth	30 m max. (20 m typical)	30 m
	rpm	100-200, usually 130-170	10-40
	Productivity/ output	2-3 m/min (penetration) 0.6-0.9 m/min (withdrawal) 400-1000 lin m/shift (0.6 m diameter)	0.4 m/min penetration 0.6 m/min withdrawall 39 m/8-h shift
Mix Design *(depends on soil type and strength requirements)*	Materials	Cement and lime in various percentages (typically 50:50 or 75:25)	Dry cement (most common), lime, max. grain size 5 mm
	w/c ratio	NA*	NA*
	Cement factor (kg_{cement}/m^3_{soil})	23-28 kg/m (0.6 m diameter), typically 40 kg/m (0.8 m diameter); overall 20-60 kg/m i.e., 80-150 kg/m^3	150-300 kg/m^3
	Volume ratio (Vol_{grout}:Vol_{soil})	NA*	NA*
Reported Treated Soil Properties	U.C.S.	Varies, but typically 0.2-0.5 MPa (0.2-2 MPa possible). Shear strength 0.1-0.30 MPa (up to 1 MPa in field)	1.8-4.2 MPa (avg. 2.5 MPa)
	k	For lime columns, k = 1000 times higher than the k of the clay; for lime-cement columns, the factor is 400 to 500.	ND*
	E	50 to 200 x U.C.S.	1 to 2.66 x 10^3 MPa (clays) 3.125 x 10^3 MPa (sandy soils)
Specific Relative Advantages and Disadvantages		Same as for DJM. Excellent Swedish/Finnish research continues.	No spoil, uniform mixing, automatic control of binder quantity. System allows for "possibility of injecting water during penetration."
Notes		Developed by Swedish industry and Government, with first commercial applications in mid 1970s, and first U.S. application in 1996.	Developed by TREVI in Italy in late 1980s. Trevi-ICOS, U.S. licensee, in Boston, MA
Representative References		Holm (1994); Rathmeyer (1996)	Pavianni and Pagotto, 1991; Pagliacci and Pagotto, 1994

*ND = No data; NA = Not applicable.

As noted by Taki and Bell (1997), when considering and comparing the data provided for each technique, several points must be borne in mind:

Firstly, a technical goal of any DMM operation is to provide a uniformly treated mass, with no lumps of soil or binder, a uniform moisture content, and a uniform distribution of binder throughout the mass. The most important construction requirements are common to each variant, and are, therefore:

- A thorough and uniform mixing of the soil and binder throughout the designated treatment area.
- Appropriate water/cement ratio (where applicable).
- Appropriate grout injection ratio (i.e., volume of grout/volume of soil to be treated) or equivalent ratio for dry binder. This, in turn, requires close coordination between drill penetration/ withdrawal rates, and the rate of grout injection.

Secondly, although these various DMM techniques as pioneered in Japan, Scandinavia, the United States, and Europe are clearly part of the same family, and similar in overall concept, there are major and significant regional and procedural variations. Clearly, each of the methods described in Appendix 1, has been developed with the intention of best satisfying these goals within the framework of the particular market challenges and restrictions and should not be regarded as equivalents. For example, those methods and techniques (WRS, WRE, WJE) that use wet binder typically are designed to produce UCSs of treated soil exceeding 1 MPa. An exception is FGC-CDM where lower strengths are deliberately engineered. In contrast, DRE columns in Japan usually have a minimum strength goal of 0.5 MPa, while similar types of columns in Scandinavia typically only need to observe a 0.15-MPa minimum criterion. Such differences in strength naturally generate corresponding differences in the relative stiffness of treated soil masses (as in block ground treatment applications) and composite soil/treated soil systems (as in in situ reinforcement applications). Furthermore, treated soils in Scandinavia using the DRE principle are often regarded as providing vertical drainage, while soils treated by other methods in other countries are usually regarded as being relatively impermeable.

Thirdly, there are important considerations related to the sampling and testing of treated soil. Terashi (1997b) summarized the factors influencing the strength of treated soil (Table 4). With respect to temperature, this is related to the size of the treated soil mass, as well as the quantity of binder introduced. In laboratory testing, there is no way to vary and simulate factors III and IV from Table 4, except for the amount of binder and the curing time. Laboratory testing therefore standardizes these factors, with the result that the strength data obtained during testing are "not a precise prediction," but only an "index" of the actual strength. Likely field strengths can then be estimated using empirical relationships established from previous projects.

Table 4. Factors affecting the strength increase (Terashi, 1997b).

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.

With respect to the data presented in Appendix 1, the following additional general points are of importance:

- New methods, refinement of existing methods, and developments in materials (e.g., use of flyash, gypsum, or slag in slurries) are continually underway.
- 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 greater than 2, although the actual in-place w/c ratio will depend on any "predrilling" activities with water, or other fluids and the permeability of the soil. Most recently, dispersants (Gause, 1997) have been 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 advantageous in certain "difficult" geographic locations), the cement injected is typically in the range of 100 to 500 kg/m^3 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 more than 200% moisture content), typically 100 to 300 kg of dry materials/m^3 of treated soil are used, providing strengths depending very much on soil type 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 5. It must be remembered that techniques can be developed to specifically provide higher (or lower) strengths or lower permeabilities, and thus the figures cited in Table 5 are gross ranges only.
- There is a dearth of information on drained shear strengths of treated soils, especially when compared to the abundance of data from unconfined compressive testing. Such drained data are valuable for use on projects with long anticipated or required useful lives (e.g., 100-year flood applications).

Table 5. Typical data on soil treated by deep mixing.

U.C.S.	0.2 - 5.0 MPa (0.5 - 5 MPa in granular soils) (0.2 - 2 MPa in cohesives)
k	1 x 10^{-6} to 1 x 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-year U.C.S. to 60-day U.C.S. may be as high as 3:1. In general, grouts with high w/c ratios have lower long-term strength gain beyond 28 days.

CHAPTER 6. INTERNATIONAL MARKET REVIEW

The purpose of this chapter is to provide a general perspective of the market conditions, the competitors, the prices, and so on, in each of these major areas of use – the United States, Japan, and Scandinavia. The sources include published data, interviews with local specialists, and other verbal inputs from conferences, short courses, and general discussions. As for chapter 3, all figures for this chapter are provided at the end of the chapter.

6.1 United States

Research for this report has identified the following contractors with DMM capability or experience (in alphabetical order). Category A contractors are essentially U.S.-owned, offer other geotechnical and/or environmental services also, and appear to have no involvement in or dependence on foreign resources* or licenses. Category B contractors are either wholly-owned U.S. subsidiaries of foreign companies, or operate only and exclusively under foreign license in the United States. Technical details of these companies and their systems are provided in chapter 5.

<u>Category A</u>

- Condon-Johnson and Associates (Oakland, CA)
- Geo-Con, Inc. (Pittsburgh, PA)
- Hayward Baker, Inc. (Odenton, MD)
- Inquip Associates (McLean, VA)
- Millgard Corporation (Medford, MA)
- Terra Constructors (Denton, TX)

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* Hayward Baker, Inc. is a Keller Company, whose ultimate administrative and financial base is in England. However for the sake of this review, it may be regarded as a U.S. corporation.

Category B

- Raito, Inc. (Burlingame, CA)
- SCC Technology, Inc. (San Francisco, CA)
- SMW Seiko, Inc. (Hayward, CA)
- Stabilator USA, Inc. (Queens, NY)
- Trevi-ICOS Corporation (Boston, MA)

Condon-Johnson and Associates acquired the license for the GeoJet system (*Engineering News Record*, 1996) from the inventor Lonnie Schellhorn for the seven western states, and invested heavily in quickly bringing two complete units to full operational status. Several major projects have already been executed in the Bay Area for applications involving pile construction, earth retention, and slope stabilization.

Geo-Con, Inc. developed the first U.S. technologies in 1988 and 1989 (DSM and SSM) following their liaison with SMW Seiko, Inc. at Jackson Lake Dam, WY. They own several rigs of different sizes, types, and capacity, suited to their traditional applications of cut-offs and hazardous waste remediation. More recently, Geo-Con has developed various earth-retention applications and arguably remains the country's most active contractor in DMM in works outside Boston, MA.

Hayward Baker, Inc. has progressed by the in-house development of a number of DMM variants for shallow and deep mixing, largely leveraging their knowledge and resources in grouting technologies. Principal applications have been for ground treatment and hazardous waste remediation.

Inquip Associates provides a DMM system called Rotomix, technologically similar to Geo-Con's SSM variant, and traditionally has focused on environmental applications. They claim to have been one of the first DMM contractors "to use modified caisson-type equipment for soil stabilization." They also have a variety of "lineal" methods for installing thin, treated soil membranes.

Millgard Corporation has been active in hazardous waste remediation via their registered WRE technique "MecTool" since 1992, and has an increased interest in geotechnical applications. This technique won the 1993 NOVA award for construction innovation.

Terra Constructors was formed in 1995 by former Geo-Con employees using resources from Texas Mechanical Contractors. They focus on environmental and hydraulic cut-off applications. They have conducted a small number of projects using their SAM method and claim capability with a MAM (Multi-Auger Mixing) method, although no case histories have been reported.

Raito, Inc. was established in early 1998, involving senior personnel from SMW Seiko, Inc. This is a subsidiary of the major Raito Kogyo Co. of Japan, who offer a wide range of DMM variants, including DJM, CDM, RSM, and SWING.

SCC Technology, Inc. was established in 1992 by another ex-SMW Seiko, Inc. executive, and is the licensee of the Tenox Corporation of Japan. Several small jobs have been executed for structural and earth support in the Bay Area, in conjunction with local mechanical resources.

SMW Seiko, Inc. was established in 1986 as the licensee for Seiko Kogyo Co., Japan, and had its first major project in 1987 in a joint venture with Geo-Con, Inc. at Jackson Lake Dam, WY. Many large projects have followed for hydraulic cut-offs and earth retention, usually in a joint venture with one or more general or specialty contractors, such as Kajima and Nicholson, respectively. Several rigs are operated. Seiko can claim the largest current volume of geotechnical DMM applications of any U.S. contractor, principally due to their involvement in the Central Artery projects in Boston, MA.

Stabilator USA, Inc. was established in 1996 as the U.S. branch of Stabilator of Sweden. Stabilator is a wholly owned geotechnical subsidiary of SKANSKA, who also owns the Slattery Company (Long Island, NY). In turn, Stabilator USA, Inc. shares a working relationship with Underpinning and Foundations Co., themselves a Division of Slattery Co. Lime cement columns to date have been installed on projects from New York to California, with the project at I-15, Salt

Lake City, being the largest. There is understood to be two sets of equipment currently in the United States, and a third is projected soon.

Trevi-ICOS Corporation commenced operations in Boston, MA in 1997, and offers WRS and DRE options in the geotechnical market, based on technology developed by the Italian-based parent, Trevisani.

Regarding the annual volume of the U.S. geotechnical market, the authors estimate that the average volume from 1986 to 1992 was in the area of \$10 to 20 million, fluctuated considerably, and showed no consistent growth trend. Between 1993 and 1996, this annual volume rose steadily by at least 50% as the impact of the major highway works in Boston and the Bay Area was felt. However, from 1997 onwards, the annual volume (until 1999 at least) will be on the order of \$50 to 80 million, reflecting an even more intense phase of DMM activity in these same areas, and increasingly frequent similar applications in other locations (e.g., Milwaukee, WI).

By comparison, the environmental DMM market from 1992 to 1997 was probably less than \$20 million/year. A growth potential of 5 to 10% per year is anticipated, given the trend among EPA/DOE to contain or fix hazardous materials rather than remove and replace them.

Unit DMM costs may be expected to vary from \$100 to 250/m^2 of lineal structure or \$50 to 100/m^3 of ground actually treated (depending greatly on a number of factors). Mobilization/ demobilization costs for larger DMM systems are typically \$80,000 to 200,000 per Deep Mix unit, but may be as low as 10% of that figure for smaller scale DMM machines, such as used for lime cement columns, or SCC.

6.2 Japan

The level of DMM activity in Japan remains by far the highest in the world. Building upon the government-sponsored research work in 1967, full-scale DMM systems have been used commercially since 1974 and appear to have grown quickly in annual volume since the early 1980s. The Japanese contractors, in close cooperation with the Federal Government, manufacturers, suppliers, and consultants have continued to develop and enhance DMM technology in response to technical and commercial challenges, such as for participants in CDM, DJM, SWING, and Mixed Walls. These associations promote the technology through conducting research, disseminating information, and producing design/construct manuals (CDM, 1994 and DJM, 1993).

They participate in annual national conferences such as sponsored by the Japanese Geotechnical Society at which many papers on DMM developments are presented (in Japanese). These associations also collect and publish data regarding market volume. For example, by the end of 1995, the CDM Association claimed more than 25 million m^3 of soil treated since 1977 with DMM, with 30% in the period of 1992 to 1995, and about 50% up to 1993 being for offshore applications (Figures 47 through 49). Output doubled from 1987 to 1993, and currently there are about 300 projects per year. Data are also shown on the Japanese involvement in China (in 1997, well over 1 million m^3). The DJM Association recorded about 16 million m^3 of ground treatment from 1980 to 1996 in 2,345 separate projects, with an estimated annual volume approaching 2 million m^3 (Figures 50 through 52). By 1994, SMW Seiko, Inc. had installed about 12.5 million m^2 of wall since 1967 (7 million m^3), in more than 4,000 projects, the vast majority of which were in Japan. In 1997, the Tenox Company reported a total of 9,000 projects completed with the SCC method since 1979 (1,000 in the first 10 years), and an estimated annual value of $100 to 200 million for their methods (principally in Japan).

Making certain broad assumptions, it would therefore seem that well in excess of 5 million m^3 of soil are treated annually using the various DMM methods, which would suggest (based on a figure of \$50 to 100/m^3 of actually treated soil) an average annual market worth of at least $250 to 500 million.

Regarding DMM applications, Figures 47, 48, and 49 represent data from the CDM Association (1993). It may be assumed that, by far, the greatest proportions of the applications are related directly to seismic mitigation. Given the historically very strong domestic market, Japanese contractors traditionally operated overseas only on projects of particularly large scale, or where Japanese funding created the appropriate financial and technological security. A notable exception was the early course taken by Seiko Kogyo Co. in setting up a U.S. subsidiary in 1986 to realize the untapped potential of the U.S. domestic market. In recent years, with the relative changes in the strengths of the national economies, Japanese specialty contractors appear to have begun to follow Seiko's lead and have established U.S. bases (e.g., Tenox and Raito). The presence in the United States of strong Japanese general and heavy civil contractors (e.g., Kumagai, Ohbyashi) has also proved to be an advantage in several ways, not the least by offering financial and cultural support.

Relative to Scandinavian practices, it is clear that Japanese DMM technology is characterized by a wide range of larger scale equipment intended to best serve the needs of large projects associated principally with tunneling and seismic mitigation. The ground to be treated is, in general, coarser and deeper than in Scandinavia, although the marine clays are highly plastic and the natural water content is at or above the liquid limit. So, in comparison with Scandinavian practice, machines are more powerful so as to provide larger diameter treatments to greater depths (often in marine environments). Higher binder concentrations are used to provide higher early and long-term strengths. In this regard, the Japanese literature shows a far wider scatter of test data from field sources than in Scandinavia, and these data appear to be significantly lower than laboratory results on similar materials.

Elsewhere in the region, DMM activity has been frequently reported in China, originally featuring Japanese specialists, but lately with domestic resources. Japanese contractors are also known to have operated elsewhere in Southeast Asia, such as in Taiwan (Liao et al., 1992) and Hong Kong.

6.3 Scandinavia

Like the Japanese, the Swedes began researching in 1967 via a series of laboratory and field tests. The original co-workers included the Swedish Geotechnical Institute, private consultants, and piling companies. This cooperative model has endured, and a wealth of information has been generated about the technical and commercial aspects of the lime cement column method in Sweden, and also in Finland, principally by the Swedish Geotechnical Institute.

The application focus remains on ground improvement and soil/pile interaction solutions for very soft, highly compressible clayey and/or organic soils. Relatively light and mobile equipment is used typically to produce columns of up to 0.8 m in diameter to relatively shallow depths (25 m). Column UCSs are typically about 0.15 to 0.2 MPa. The main application is for settlement reduction under road and rail beds and embankments (Figure 53).

Annual production data are provided in Figures 54 through 57, showing an exponential growth in usage since 1989 (even despite quiet national economies), and an almost total use now of lime and cement as binders. The drop in production after 1994 (Figure 58) has corresponded to a general downturn in the national economies, except for road construction. In contrast, during 1994, there were some major projects in Sweden that rapidly increased demand. Additional data on Finnish and Swedish practices are provided in Appendix 2, based on a visit made by the writer to specialists in both countries.

In <u>Sweden</u>, there would appear to be four major national competitors (plus two or three Finnish contractors), with the following estimated mechanical capacities:

- L.C. Marktechnik – 8 to 10 machines
- Stabilator – 6 to 8 machines (plus at least as many overseas)
- Fondatur – 3 to 5 machines
- Hercules Grundlaggning – 4 machines (although *European Foundations* (1998) claims them "to be the largest foundation contractor in Sweden")

In addition to Stabilator's overseas involvements, principally in the United States and Southeast Asia, Hercules recently (*Ground Engineering*, 1998) announced a joint venture with Stent Foundations for lime cement column work in the United Kingdom (Appendix 3), although traditionally the bulk of their work has been in Scandinavia.

Holm (1997) estimated that there was a total of about 30 machines working throughout Scandinavia. The estimated current annual production of about 4 million lineal m (1.2 million m^3) is worth about \$30 to 40 million. Most projects have in excess of 30,000 lineal m of columns. Materials are typically 35 to 50% of the contractors' costs; however, both lime and cement are readily and cheaply available in Sweden. Work is typically conducted according to prescriptive plans and specifications; however, increasingly, alternative proposals are proving to be acceptable and design-build concepts are growing. A forecast of production in the coming years is provided in Figure 58.

The milestones of Swedish practice are described in Chapter 2, and are elaborated upon by Porbaha (1998). However, particular attention is being drawn to the Swedish Deep Stabilization Research Center, which was established in 1995, to continue intensive research work for an additional five years involving a nationwide consortium of interested parties (Appendix 4).

Data for Finland are shown in Figures 54, 55, and 59, confirming a similar rapid growth from the late 1980s. The integrated engineering efforts of the nation are reflected in the new research consortium established for the ongoing Structures Research Programme (TPPT), lasting from 1995 to 2001.

The three major contractors appear to be:

YIT Corporation -	The largest, having developed its own system (Appendix 2); owns four rigs. Research continues into a "two tanks" (for binder components) method, and deeper penetration capability. Also operates in Sweden and Norway. Average annual DMM volume is \$4 to 5 million. Owned by the largest Finnish general contractor.
Sillaupäa:	Owns three rigs, using the Stabilator system.
RRP:	Owns three rigs.

Although most of the Finnish work uses lime and cement binders, increasing use is being made of "secret binders," such as those including gypsum, since both lime and cement are relatively expensive, having to be imported. Such materials may constitute as much as 50 to 60% of the total installation cost, while slag is much more readily and cheaply available, bearing in mind Finland's iron and steel industrial base.

The overall market is growing as the economy strengthens. As in Sweden, more than 90% of the volume (about 1.5 million lineal m/yr) is for settlement reduction. The balance is for the installation of "wall panels" for slope stabilization. Prior to 1989, piling, band drains, replacement, and lightweight fills were used in these applications instead.

There is no national design or construction code, but the Road Administration has produced its own new specifications (Appendix 5), and most practitioners follow these. All work is awarded on the basis of such prescriptive specifications to the low bidder. Mobilization/demobilization costs per rig are about \$50,000 to 75,000, and columns are typically \$7 to 10/lineal m. Most projects are worth less than \$500,000, and the national value is around \$15 million/year, principally in projects around Helsinki and to the west.

The Finns are also actively pursuing the "Mass Stabilization" method, which employs lime and cement to treat organic upper horizons (Appendix 6). This process provides vertical and horizontal mixing and is done after the lime cement columns have been formed, thus, in effect, creating a pile-supported raft structure.

In other parts of the region, columns have been installed in <u>Norway</u> since the mid 1980s under the guidance of the Swedish Geotechnical Institute, and using Swedish contractors. The applications have principally been for excavation support and environmental remediation in the Oslo area. Very little native research has been conducted. The market size until 1993 was minimal (two or three small projects per year), but has increased rapidly in the later 1990s due to roadway and airport developments. The total volume is estimated now at around 500,000 lineal m/year.

It is also known that Finnish and Swedish contractors are exploring opportunities in the <u>Baltic</u> countries and <u>Poland</u>, although few case histories have yet been recorded. Porbaha et al. (1998) reports that in <u>Bulgaria</u>, the Academy of Sciences has conducted some research on soil-cement and DMM technology in the rehabilitation of railway embankments.

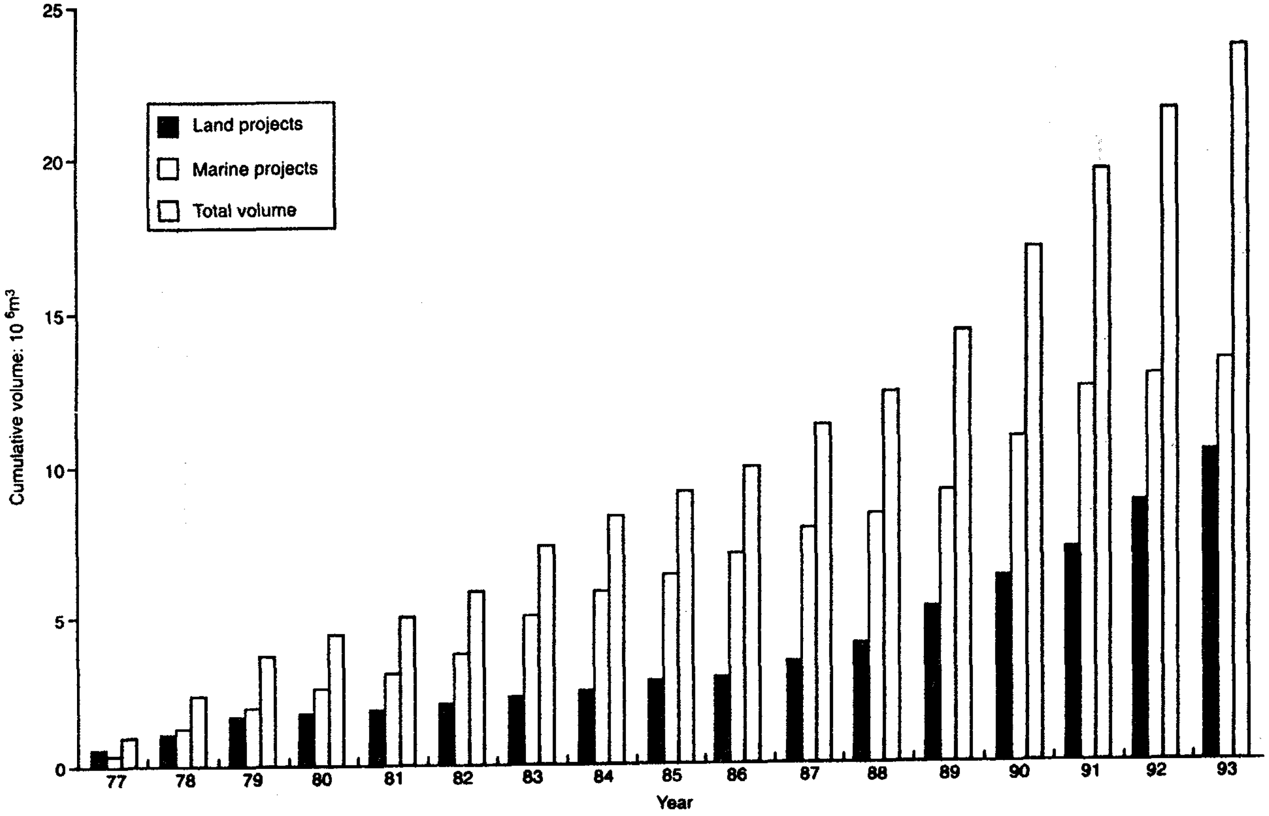

Figure 47. Volume of soils treated by CDM method for land and marine projects in Japan (data from Okumura, 1996).

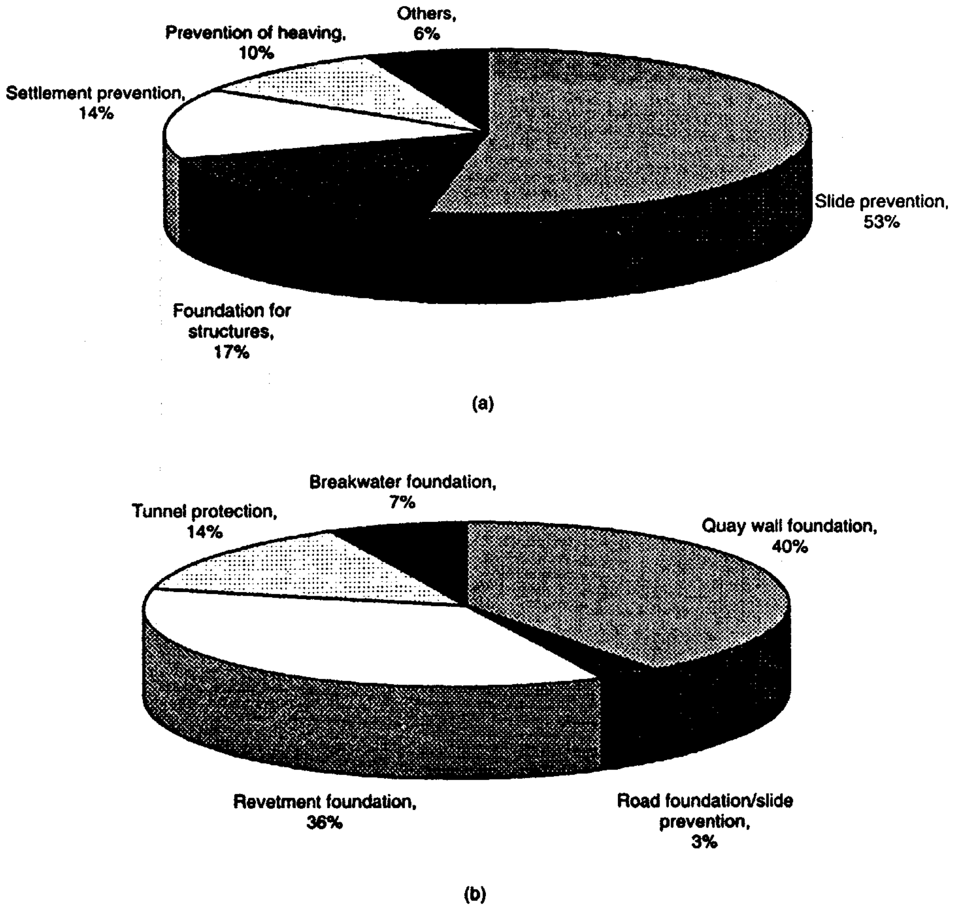

Figure 48. Applications of DMM projects using CDM in Japan: (a) land projects and (b) marine projects (data from the CDM Association, 1994).

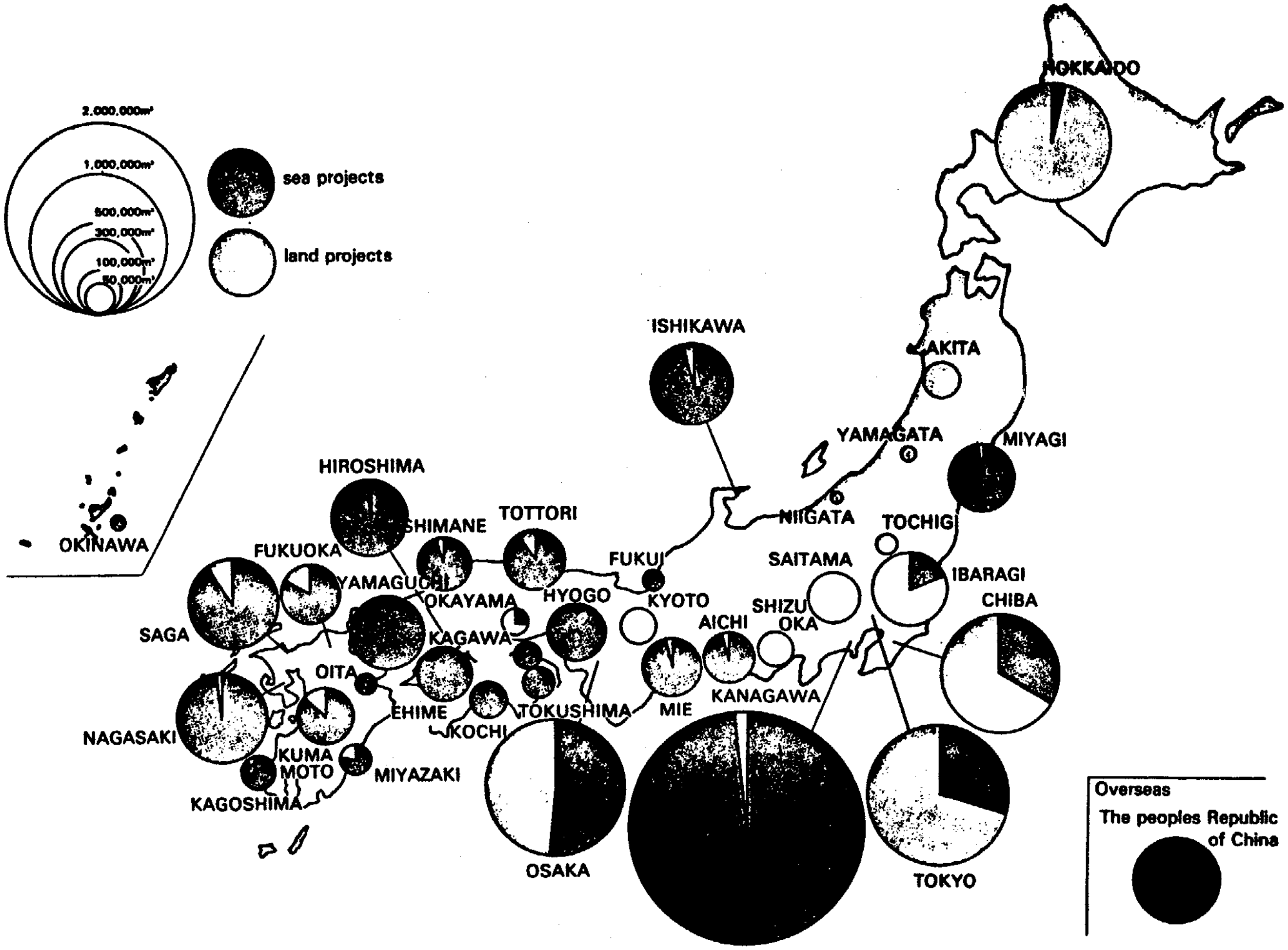

Figure 49. Location of CDM projects in Japan and China until 1993 (CDM Association, 1994).

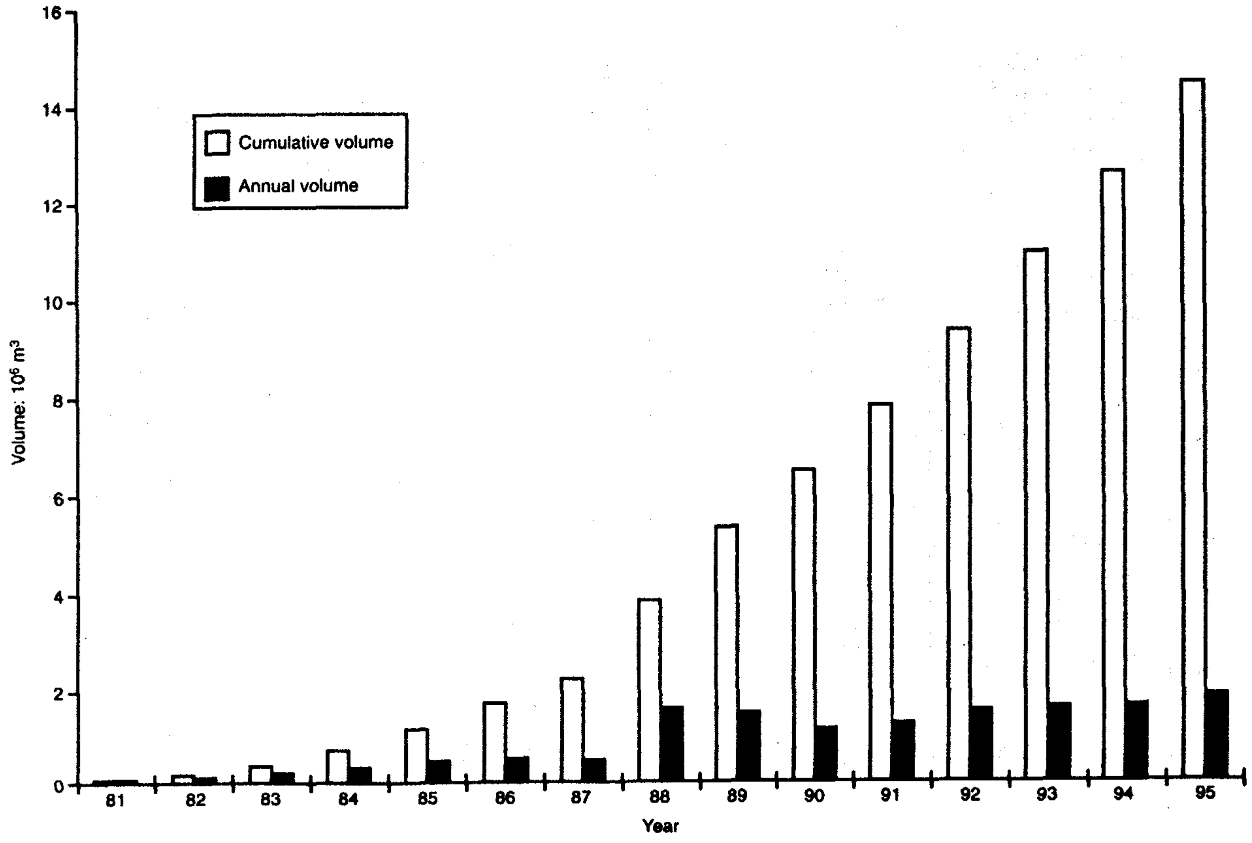

Figure 50. Volume of soils treated by the DJM method in Japan (1981-1995) (data from Okumura, 1996).

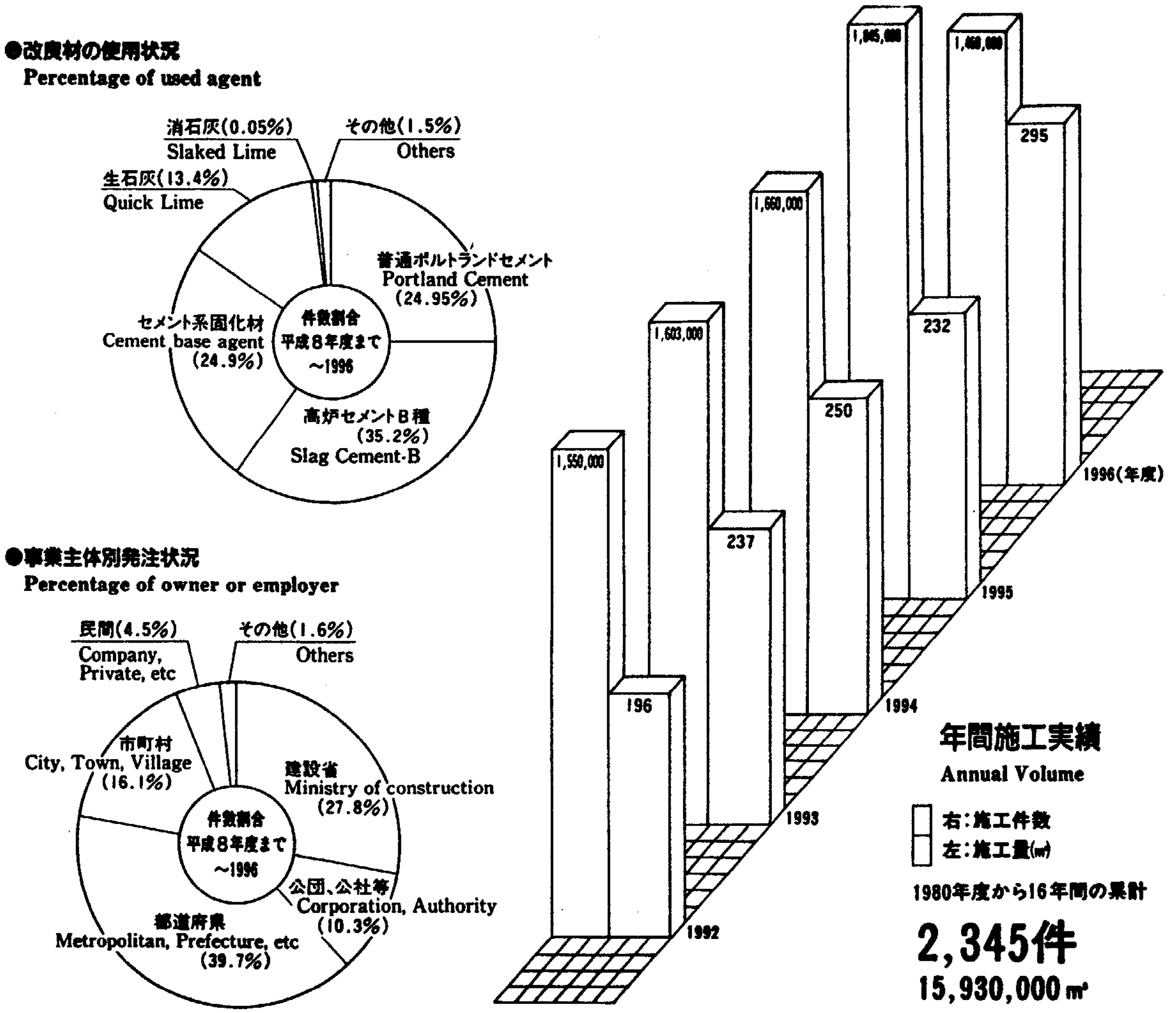

Figure 51. Data on DJM usage in Japan (1992-1996). [Left bar represents volume (m^3) and right bar represents number of projects] (DJM Association, 1996).

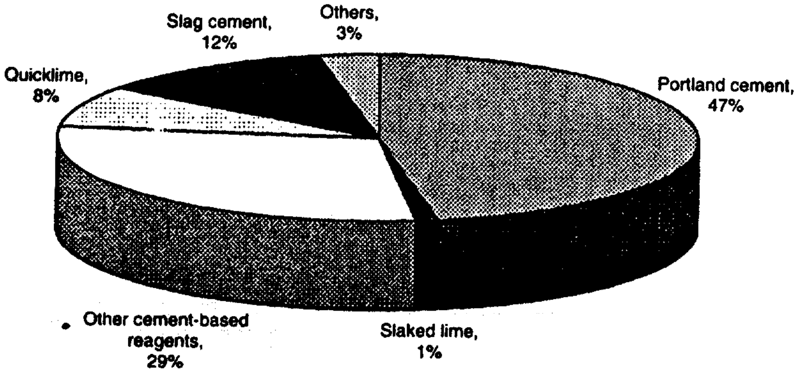

Figure 52. Type of binders used in Japan (data from DJM Association, 1993).

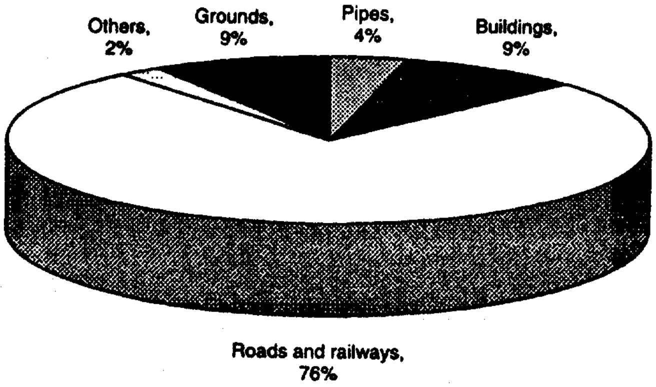

Figure 53. Applications of lime cement columns in Sweden (1990-1991) (data from Åhnberg et al., 1995).

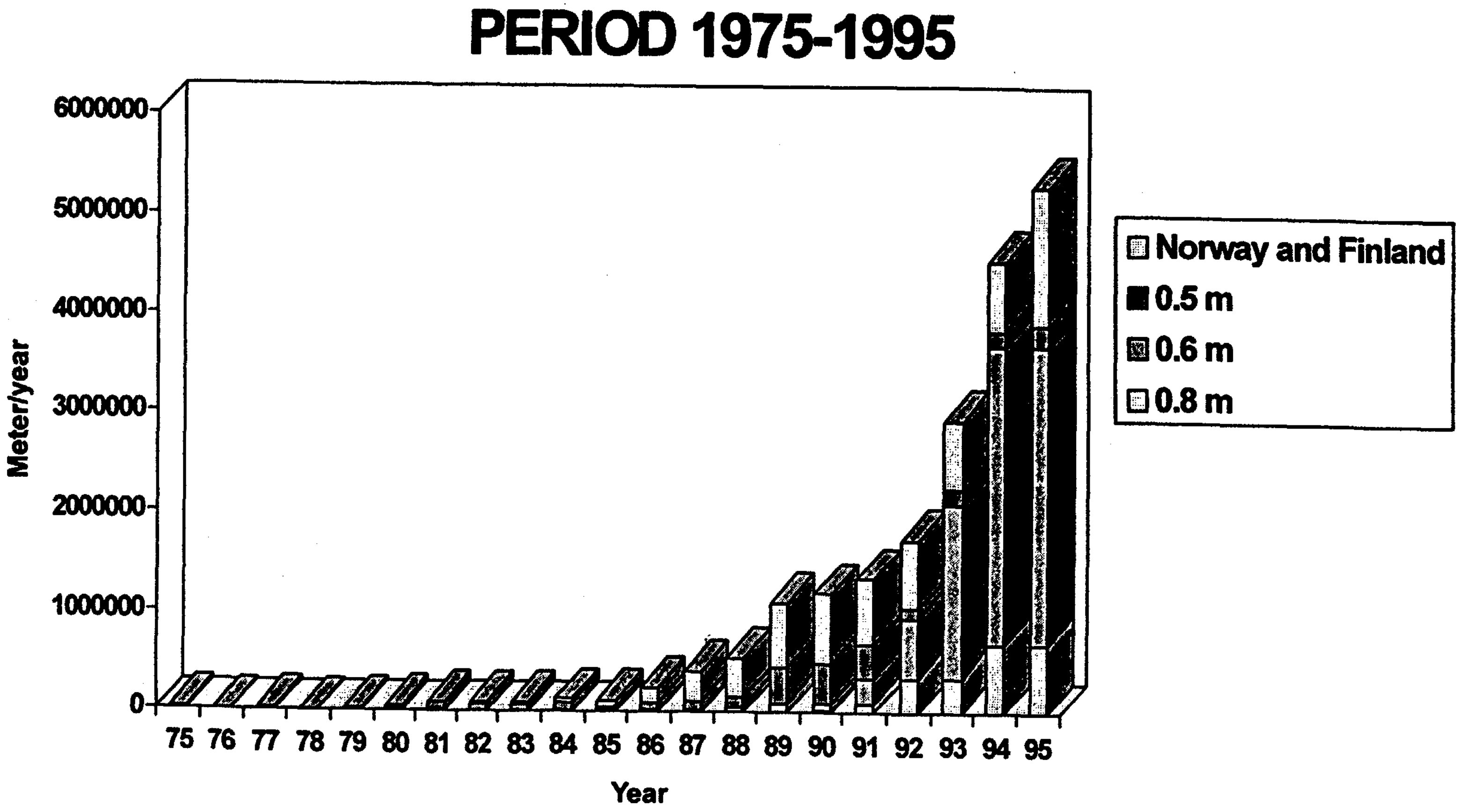

Figure 54. Production data for Scandinavian countries based on column diameter (Stabilator USA, Inc., 1998).

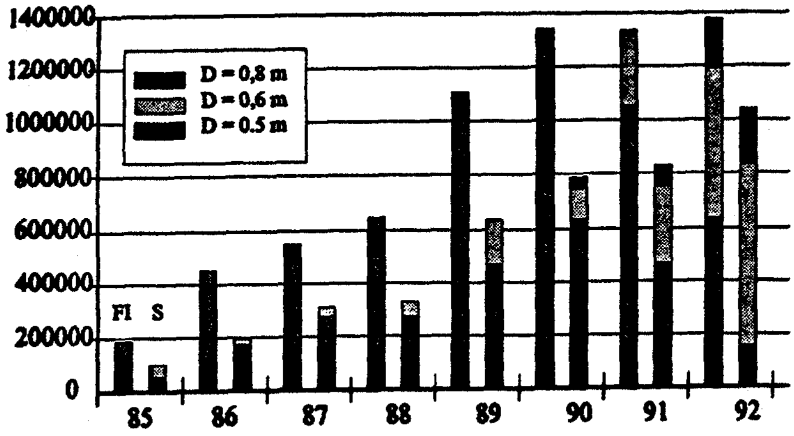

Figure 55. Volume of deep mixing (m^3) in Sweden and Finland based on column diameter (Rathmeyer, 1996).

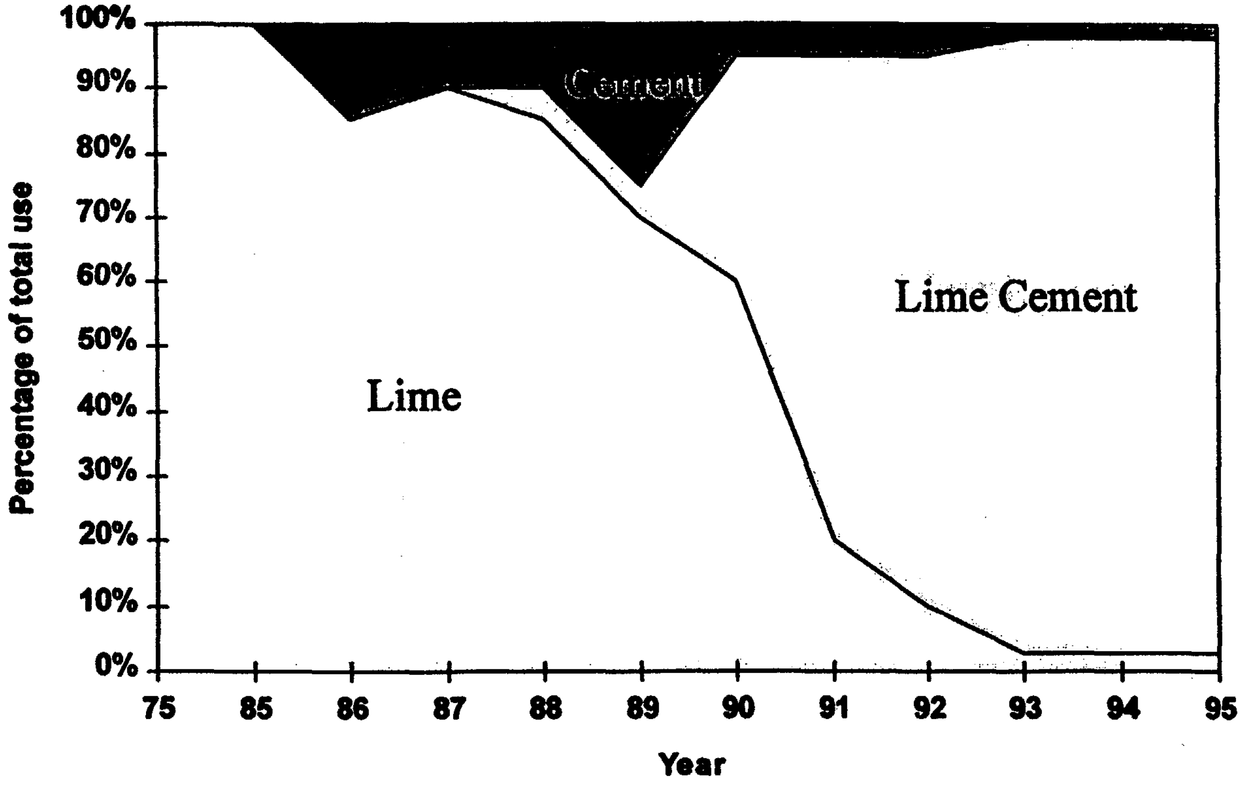

Figure 56. Changes in use of binders in Scandinavia (1975 to 1995) (Stabilator USA, Inc., 1998).

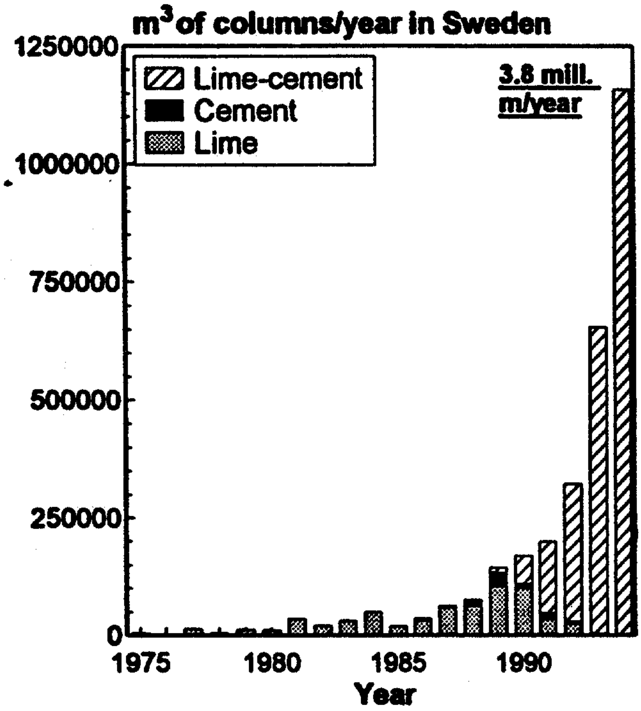

Figure 57. Changes in use of binders with time, based on Swedish output (1975-1994) (Åhnberg, 1996).

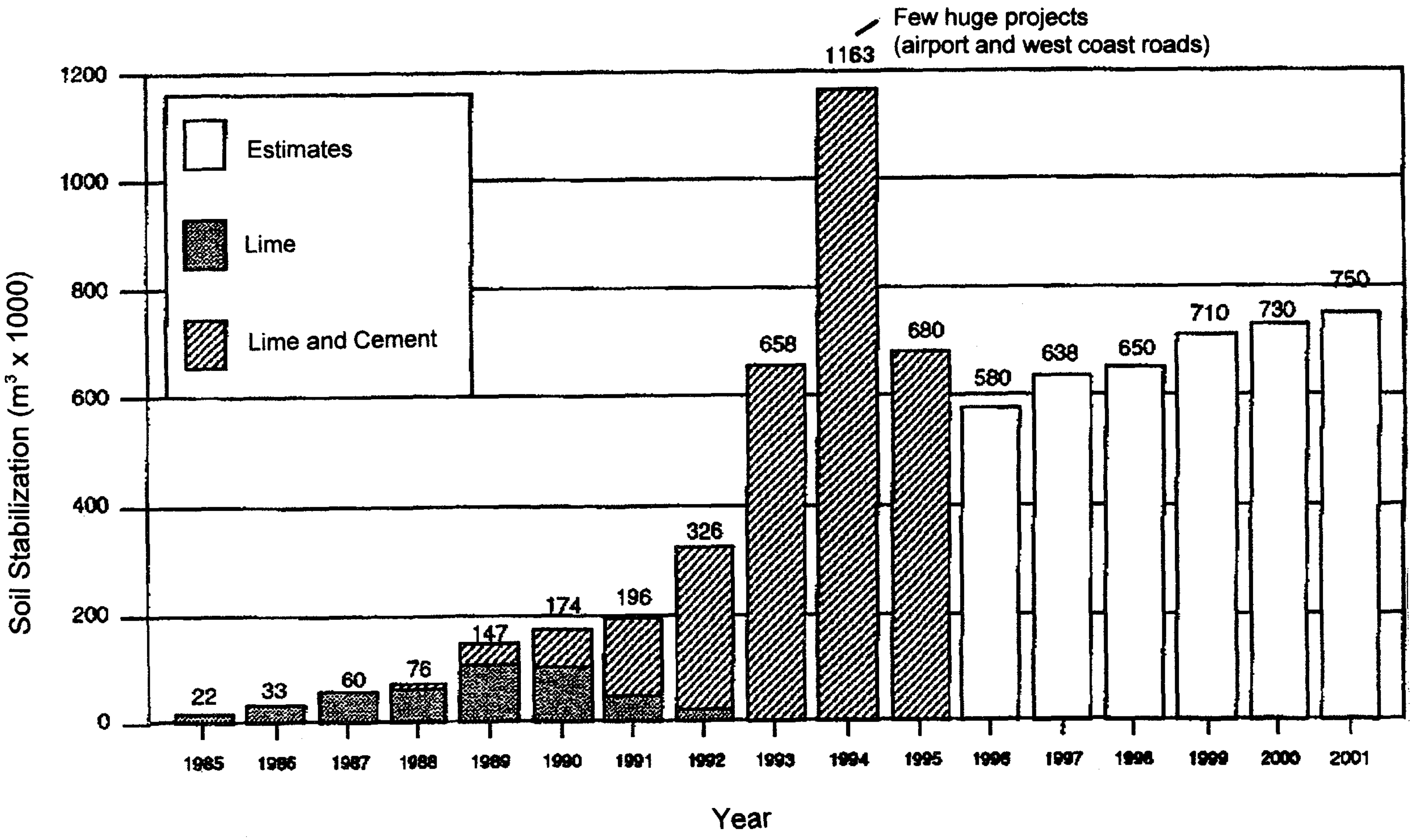

Figure 58. Details of lime cement column production in Sweden (Finnish Technical Development Center, 1996).

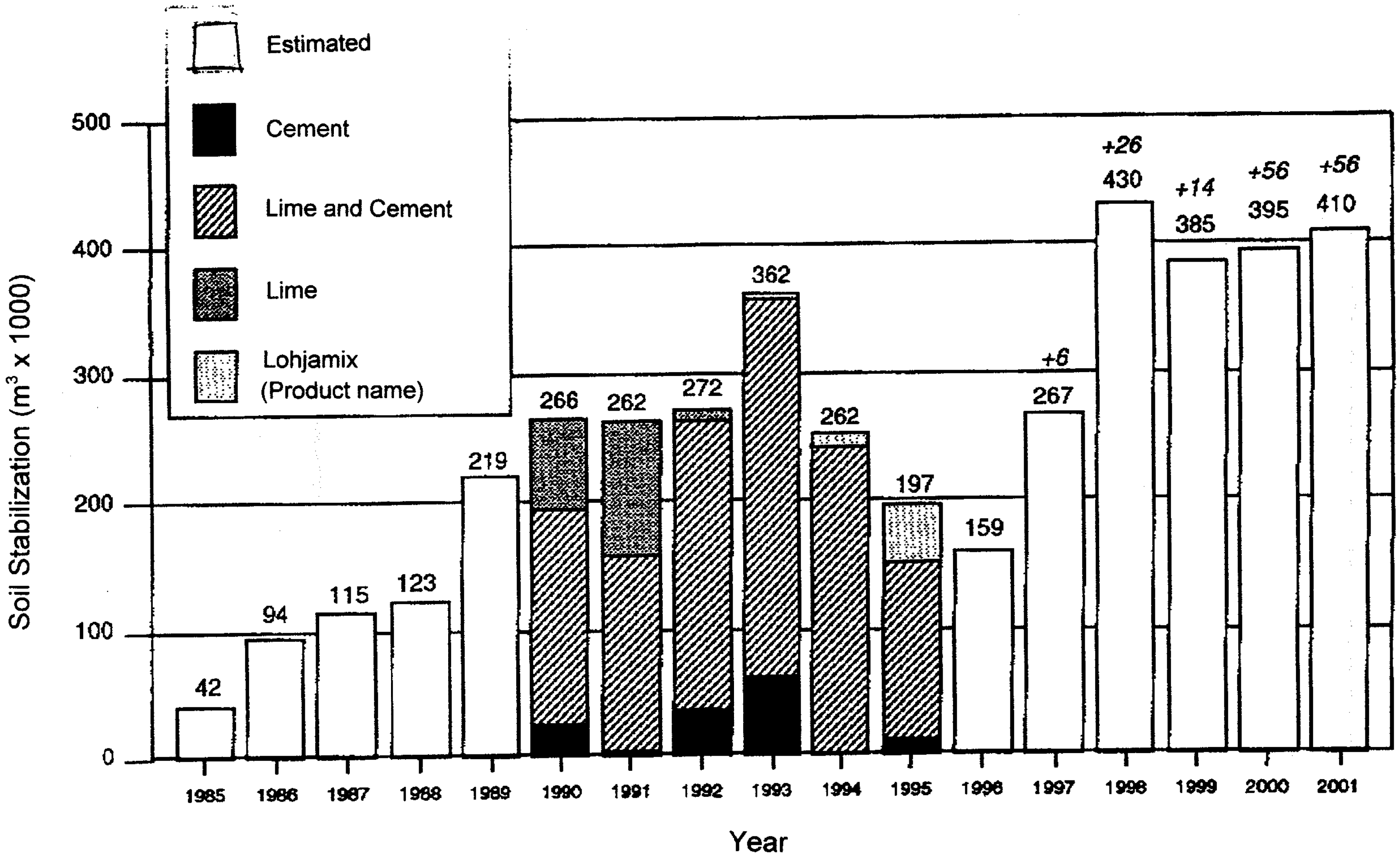

Figure 59. Details of lime cement column production in Finland (Finnish Technical Development Center, 1996).

CHAPTER 7. BARRIERS TO ENTRY AND LIMITS TO EXPANSION WITHIN THE UNITED STATES

Despite the benefits and advantages of DMM techniques illustrated in the previous chapters, the number of DMM applications had a relatively slow rate of growth in the United States until 1992. Thereafter, growth was rapid, principally due to major projects in Boston, MA, and the Bay Area of California. It is possible to identify several, often interrelated, factors that have conspired to act as barriers to market entry for prospective contractors, and as potential limits to market growth in the United States. These include:

- Demand for the product.
- Awareness of the product by specifiers and other potential clients.
- Bidding methods/responsibility for performance.
- Geotechnical limitations.
- Technology protection.
- Capital cost of startup.

7.1 Demand for the Product

DMM was developed in countries where there were urgent national requirements to somehow remediate soft foundation soils to reduce settlements, lateral movements, liquefaction potential, and seepage. In the United States prior to the mid 1980s, these were problems that were satisfied by relocating the project, using other technologies, or by simply choosing to ignore the potential consequences. However, the last decade in the United States has seen a focus on urban construction and rehabilitation, acute reminders of the impact of seismic activity, and a pressing need to protect the environment against the consequences of industrial and urban pollution.

As illustrated in chapter 3, DMM is a well-proven technology to serve each of these demands: stabilization, retention, and improvement of soils in urban environments; liquefaction mitigation; and hazardous waste and water control. Given projected construction market trends in the

United States, it may reasonably be forecast that demand for DMM will continue to increase rapidly for these applications in particular.

7.2 Awareness of the Product

Contemporary DMM was introduced into the United States in 1986, and for many years was associated principally with the activities of two companies. A combination of factors, including linguistic, cultural, financial, and promotional factors, contributed to the fact that the considerable, broad engineering advantages of DMM did not receive the national recognition that they merited in the engineering community at large. There are recent clear signs that this has changed, and there is no doubt that levels of awareness of DMM in the engineering community are now considerably higher. This is due to the efforts of a wider number and quality of specialty contractors and consultants, more prolific technical publications, short courses, and the coincidence of a number of very high-profile DMM projects across the country.

7.3 Bidding Methods/Responsibility for Performance

Specialty geotechnical processes, especially those that can be used in applications that may be accomplished by several different proprietary techniques, are often difficult to specify under a prescriptive type of specification. This is especially true of the newer, emerging processes, although the growing awareness of DMM in the engineering community referred to in Section 7.2 above has permitted certain major projects to be successfully specified, bid, and constructed in this fashion. However, given the rapid development of the various "means and methods" of DMM technology, it appears more appropriate that it be bid as a response to a performance-type specification wherein the project conditions and objectives are identified and the bidder offers a responsive solution. This situation applies, however, only where the specifier has a good, working knowledge of the various methods and their effectiveness so that he can determine the "best buy" on a rational basis. As shown by Nicholson and Bruce (1992), this option may take different forms, such as value engineering, pre- or post-bid alternatives, and negotiated bids. These are all encompassed under the umbrella of the "design-build" concept.

7.4 Geotechnical Limitations

DMM has been developed primarily to treat relatively soft, fine-grained soils and fills, with no natural or artificial obstructions. Therefore, sites with boulders, very dense or cohesive soils, or containing previously installed structures, including piles, are not best suited to DMM. Although certain of these difficulties can be overcome technically by process enhancements, the cost of these changes may render DMM non-competitive. In this context, it is noteworthy that attempts to use DMM in the United States in relatively unfavorable conditions have met with mixed success, and one may cite the difficulties experienced in penetrating dense, cobble alluvium under a dam in Washington State, and in providing treated cohesive soils, with an acceptable degree of freeze/thaw resistance when exposed, in Massachusetts. Furthermore, DMM, in general, may only be practical to depths of around 40 m (less for lime cement columns) and thus, if the depth of treatment is to be greater, DMM may be neither practical nor economical.

7.5 Technology Protection

In general, the practitioners of DMM in the United States are (or claim to be) protected directly by their own patents, or operate as exclusive licensees of both foreign and U.S-based patent holders, as described in chapter 6. Potential new DMM contractors either have to invent their own system (increasingly difficult as the current range (chapter 5) already appears to be so comprehensive) or somehow acquire an existing technology under license or sub-license. The latter choice mainly restricts the options to certain foreign sources and, depending on the commercial terms, may render the holder at best only marginally competitive in his domestic market. In addition, there appears to be a certain atmosphere of reluctance on the part of Japanese contractors to be involved in the United States.

However, if the U.S. market does continue to prove increasingly attractive for DMM, especially at a time when European and Japanese market conditions appear to be stagnant at best, then it is logical to assume that more interest will be shown by these foreign patent holders in establishing some type of presence in the United States. Options for technology acquisition would be by license, joint venture, or acquisition, the actual form reflecting the goals of the licensor and the capabilities and resources of the particular U.S. potential licensee.

7.6 Capital Cost of Startup

For those U.S. companies that have sought to develop their own systems, the financial outlay is considerable – design and construction of a prototype, full-scale testing and field demonstration, and system promotion all have to be funded "up front." Thereafter, there may be a considerable period before the first suitable project is won, and even then, this project will be unlikely to make anticipated and/or significant profit given the "learning curve" inefficiencies that will have to be overcome on the job. The cost of obtaining a patent is small in comparison with these outlays. Based on the recent experience of one "start-up" DMM operation in California, these up-front costs, even in a wholly owned patent or exclusive license situation, may lie in the range of $1 to 1.5 million per unit. Most of the larger jobs may require several units and thus the committed capital cost may quickly rise to around $5 million or more. The depreciation of such units is typically high (around one-thousandth of the equipment value per calendar day), and thus the financial implication of having these units idle can be extremely severe. Another vital issue is the maintenance and upgrading of the equipment on an ongoing basis. If resources are not devoted to this task constantly, then the subsequent cost implications of major "makeovers" or replacement of equipment can be substantial.

In the other situations, where the U.S. contractor is simply a licensee, the initial cost of setting up is less, although regular periodic specialty equipment charges and annual license fees will still apply and accumulate regardless of how much revenue the licensee actually generates. The licensee is also still typically responsible for management, bidding, marketing, and promotion and thus has his own substantial overhead costs to further offset revenues.

7.7 Overview

It is clear that regardless of how the technology is developed or acquired – by license, joint venture, or internal development – DMM may be regarded as a particularly "cash hungry" technology, largely because of the scale and complexity of the equipment involved. This will remain the major challenge to prospective contractors, even if the other barriers listed above are removed or circumvented in response to evolving market conditions. As a final point, it may be expected that the market volume will grow even more quickly if a major natural disaster were to occur, for example, as happened in Japan following the Kobe earthquake in January 1995, and/or if the current high-profile DMM projects, especially in Boston, prove to be major technical successes. However, it may also be expected that a major technical reverse on a high-profile project will have the opposite effect on national perception and demand.

CHAPTER 8. FINAL REMARKS

The many different versions of DMM have undergone major developments and have experienced notable international success for well over two decades. These techniques have become trusted and valuable engineering tools for treating, improving, and retaining softer soils in a wide variety of applications. In the United States – arguably the birthplace of the concept – the introduction of "contemporary" Japanese-influenced Deep Mixing only occurred in 1986 (Bruce, 1996). Following somewhat erratic progress and expansion, the use of DMM is steadily and rapidly growing in the United States, mainly as a consequence of the particular geotechnical demands of urban infrastructure redevelopment in the cities of Boston, Salt Lake City, and the San Francisco Bay Area. The market is served by a relatively small number of specialists using both foreign and U.S. technologies. Start-up costs and proprietary restrictions have thus far prevented a wider competitive spectrum from evolving, despite the new-found willingness apparent among the Japanese specialists to share data and work in partnership with foreign organizations. In a similar vein, the recent commercial introduction of the Nordic DMM technology into U.S. practices, following years of academic promotion, is a fascinating development in many ways.

It is a fact that the future of DMM as a reputable and respected ground engineering tool in the United States will depend heavily on the success of high-profile projects, largely in Boston, Salt Lake City, and California. Although this may seem somewhat unfair, and in many respects rather illogical, this reality does reflect the acute awareness the industry has evolved for the technology recently, as well as the "cutting edge" passion with which its proponents have promoted it.

DMM is an extremely valuable, competitive, and useful ground engineering technology if applied correctly, designed properly, constructed efficiently, and restricted sensibly to the natural restraints of soil conditions and equipment capability. Despite its market potential, it remains a relatively costly technology for contractors to acquire, and so the number of potential competitors, within the current domestic structure, will remain correspondingly low.

Following this logic, we may therefore conclude that among the geotechnical community in the United States, DMM may well become a commodity – such are its multi-faceted attractions – but a product that can be provided only by a relatively small number of producers. The comparison with the circumstances of the petroleum production and distribution industry is close, except for the observation that the reserves of the DMM industry are not, in the fundamental sense, finite.

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